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BATTERIES IN PV

SYSTEMS

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1. Introduction

This report presents **fundamentals of battery technology** and charge control strategies commonly used in stand-alone photovoltaic (PV) Systems,**with an introduction on the PV Systems itself**. This project is a **compilation of information from several sources**, including research reports and data from component manufacturers.

Comparisons are given for various battery technologies, and considerations for battery subsystem design, auxiliary systems, maintenance and safety are discussed.

Daily operational profiles are presented for different types of battery charge controllers, providing an in-depth look at how these controllers regulate and limit battery overcharge in PV systems.

Most importantly, considerations for properly selecting batteries and matching of the charge controller characteristics are presented.

Purpose

This work was done **to address a significant need within the PV industry regarding the application of batteries and charge control in stand-alone Systems,the environmental impacts of them, if they are really applied on a big scale, what are pros and cons of each kind of battery,etc.** Some of the more **critical issues** are listed in the following:

- **Premature failure** and lifetime prediction of batteries are major concerns within the PV industry.
- Batteries experience a **wide range of operational conditions** in PV applications, including varying rates ,of charge and discharge, frequency and depth of discharges, temperature fluctuations, and the methods and limits of charge regulation. These variables make it very difficult to accurately predict battery performance and lifetime in PV systems.
- Battery performance in PV systems can be attributed to both battery **design and PV system operational factors**. A battery which is not designed and constructed for the operational

conditions experienced in a PV system will almost certainly fail prematurely. Just the same, abusive operational conditions and lack of proper maintenance will result in failure of even the more durable and robust deep-cycle batteries.

- Battery manufacturers' specifications often do not provide sufficient information for PV applications. The performance data presented by battery manufacturers is typically based on tests conducted at specified, constant conditions and is often not representative of battery operation in actual PV systems.

2. Scope and Objectives

• What are the basic battery types and classifications?

• What are the primary differences in the design and operational characteristics of different battery types?

• What are the principal mechanisms affecting battery failure and what are the common failure modes?

• What operation and maintenance procedures are needed to maintain battery performance and extend lifetime?

• What are the consequences of undercharging and overcharging for various battery types?

• How should a battery subsystem be electrically designed in a PV system for optimal performance and safety?

• What is the common terminology associated with battery charge controllers for PV systems?

• How do the rates of charge, charge regulation algorithm and set points affect battery performance and lifetime in PV systems?

• What are suggested design, selection and matching guidelines for battery application and charge control requirements in PV systems?

3.Brief History of Photovoltaics

The first conventional photovoltaic cells **were produced in the late 1950s**, and throughout the 1960s were principally used to provide electrical power for earth-orbiting satellites.

In the 1970s, improvements in manufacturing, performance and quality of PV modules helped to reduce costs and opened up a number of opportunities for powering remote terrestrial applications, including battery charging for navigational aids, signals, telecommunications equipment and other critical, low-power needs.

In the **1980s, photovoltaics became a popular power source for consumer electronic devices**, including calculators, watches, radios, lanterns and other small battery-charging applications.

Following the energy crises of the 1970s, significant efforts also began to develop PV power systems for residential and commercial uses, both for stand-alone, remote power as well as for utility-connected applications.

During the same period, international applications for PV systems to power rural health clinics, refrigeration, water pumping, telecommunications, and off-grid households increased dramatically, **and remain a major portion of the present world market for PV products.**

Today, the industry's production of PV modules is growing at approximately 25 percent annually, and major programs in the U.S., Japan and Europe are rapidly accelerating the implementation of PV systems on buildings and interconnection to utility networks.

4. How a PV System Works & Components

Simply put, PV systems are **like any other electrical power generating systems, just the equipment used is different** than that used for conventional electromechanical generating systems. However, the principles of operation and interfacing with other electrical systems remain the same, and are guided by a well-established body of electrical codes and standards.

Although a PV array produces power when exposed to sunlight, a number of other components are required to properly conduct, control, convert, distribute, and store the energy produced by the array.

Depending on the functional and operational requirements of the system, the specific components required may include major components such as a DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical load (appliances). In addition, an assortment of balance of system (BOS) hardware, including wiring, overcurrent, surge protection and disconnect devices, and other power processing equipment. Figure 1 show a basic diagram of a photovoltaic system and the relationship of individual components.

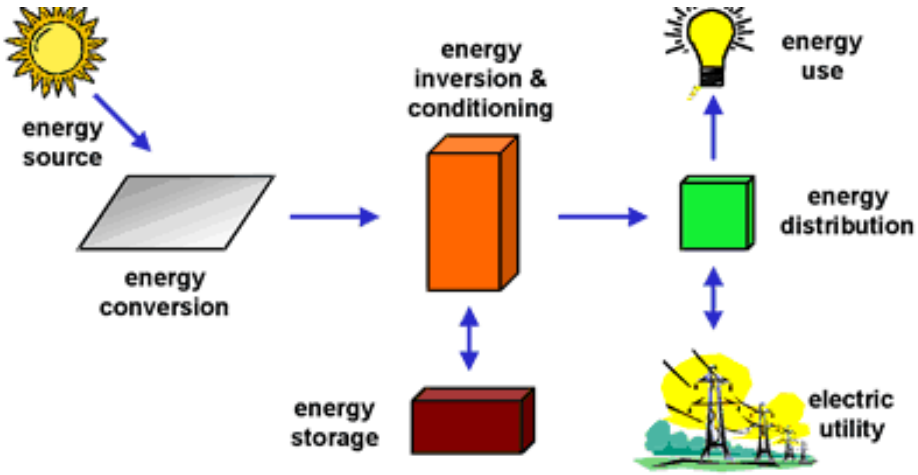

Figure 1. Major photovoltaic system components.

4.1.Components and maintenance

Photovoltaic power systems are **exceptionally *modular***, which not only provides for **easy transportation and rapid installation**, but also enables **easy expansion** if power requirements increase. PV systems for stand-alone applications may comprise some or all of the following ***basic components***:

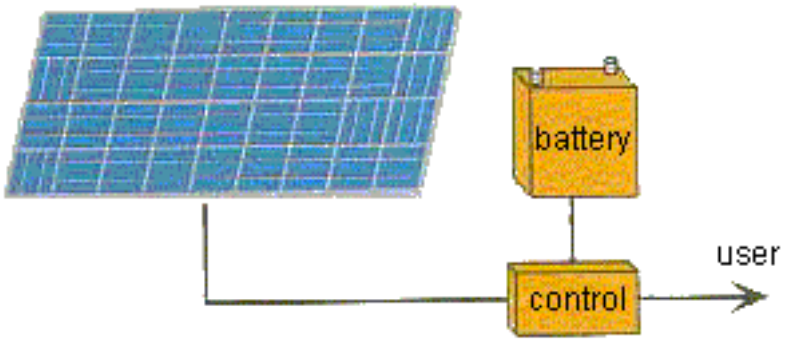

Figure 2.Scheme of a PV system

1. A **PV generator** and support structure (a single module or an array of several modules)

2. **Power conditioning equipment** (Optional - typically includes inverters and control and protection equipment)

3. **Power storage** (Optional - usually provided by batteries)

4. **Cables**

5. **A load** (e.g. lights, pumps, refrigerators, radio, television)

The solar **PV generating equipment has no moving parts**, which on the whole keeps maintenance requirements to a minimum and leads to long service lifetimes. The modules themselves are typically **expected to operate for about twenty years**, and **should not require much more than the occasional cleaning to remove deposits of dirt**.

The majority of the **other components - referred to as the Balance of Systems *(BOS)* - are generally serviceable for ten or more years** if simple preventative maintenance measures are followed. **Batteries**, which are commonly required for most off-grid applications except water pumping, **are currently the "weak-link" in the PV system and will typically need replacement every five years or so**.

It is essential that storage batteries, and indeed all system components are of an acceptable quality. Where PV systems have **failed** in the past for technical reasons, it has generally been **due to** bad system design and/or **poor selection of BOS components**, rather than to failure of a PV module. As a result, considerable **international research efforts are presently directed towards improving performance of BOS components**.

5. Costs and economics

In terms of average unit energy costs calculated **using traditional accounting techniques, PV generated electricity cannot yet compete with efficient conventional central generating plants**. **Accordingly**, the vast majority of **PV** installations to date **have been for relatively low-power applications in locations, which do not have ready access to a mains electricity grid**. In such cases, PV has been selected because it offers a secure and reliable power supply, and is often the cheapest power option.

Like any such commodity, the total purchase price of a PV system is based on all inherent costs of producing the individual components, transporting these to the site and installing them. There may also be associated costs of designing and engineering the system and purchasing land - particularly for large-scale or one-off projects.

The **total price is therefore very difficult to define**, varying with application, size of system and location. However, **the costs of the PV array are a significant factor and will typically constitute 30%-50% of the total capital cost with the BOS contributing a similar amount.**

As an example, a small domestic lighting system to power two or three fluorescent tubes would typically be in the order of 50 W, and would cost perhaps USD 500, whereas a solar photovoltaic vaccine refrigerator might require a 200 W array, bringing the total price of the system to around USD 5000.

Thus PV systems are an attractive option in rural areas where no grid-connection is available, though simple payback terms, **because of its high capital costs, PV can often appear unattractive. However, using life-cycle costing, which accounts for all fuel and**

component replacement costs incurred over the life of the system, PV often compares favorable with the alternatives, which tend to have lower initial costs, but incur significantly greater operating costs.

Displacing conventional technologies with photovoltaic systems can bring various positive effects, which are difficult to quantify in direct financial terms, but which nonetheless offer significant economic and social benefits. For instance, in comparison to traditional kerosene lamps, **PV can provide better lighting levels**, enabling educational and income generating activities to continue after dark **with reduced risk of fire and avoidance of noxious combustion fumes.** The World Health Organization has noted that PV offers a **more reliable refrigeration** service than other power supply options. This has resulted in increased efficacy of stored vaccines, which in turn has helped to reduce mortality rates. Such factors must be considered when PV is compared to the alternatives even though the cost benefits are not easy to assess.

6. Types of PV Systems

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. **The two principal classifications are grid-connected or utility-interactive systems and stand-alone systems**. Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems.

6.1.Grid-connected or utility-interactive PV systems are designed to **operate in parallel** and interconnected **with the electric utility grid**. The primary component in grid-connected PV systems is the inverter, or power conditioning unit (PCU). The PCU converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized. A bi-directional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads, or to back-feed the grid when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility .This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or repair.

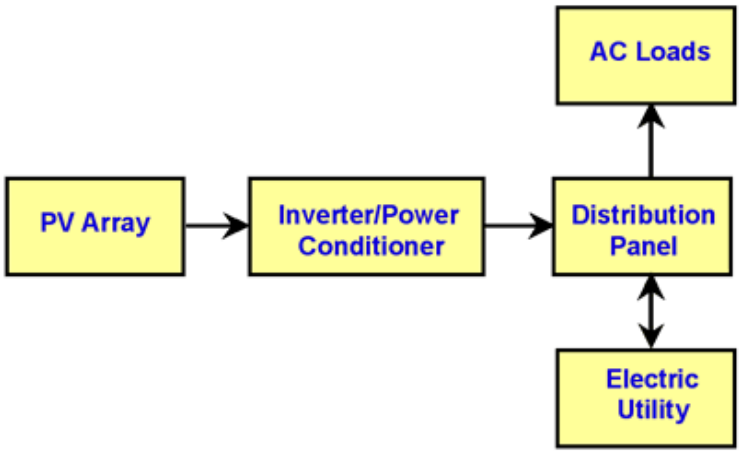

Figure 3. Diagram of grid-connected photovoltaic system.

6.2.Stand-alone PV systems are designed to operate **independent of the electric utility grid**, and are generally designed and sized to supply certain DC and/or AC electrical loads. These types of systems may be powered by a PV array only, or may use wind, an engine-generator or utility power as an auxiliary power source in what is called a PV-hybrid system. The simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load (Figure 4). Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours, making these designs suitable for common applications such as ventilation fans, water pumps, and small circulation pumps for solar thermal water heating systems. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well-performing direct-coupled system. For certain loads such as positive-displacement water pumps, a type of electronic DC-DC converter, called a maximum power point tracker (MPPT), is used between the array and load to help better utilize the available array maximum power output.

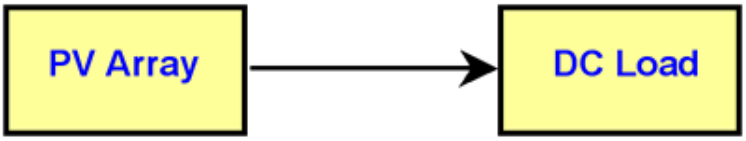

Figure 4. Direct-coupled PV system.

In many stand-alone PV systems, batteries are used for energy storage. Figure 5 shows a diagram of a typical stand-alone PV system powering DC and AC loads. Figure 6 shows how a typical PV hybrid system might be configured.

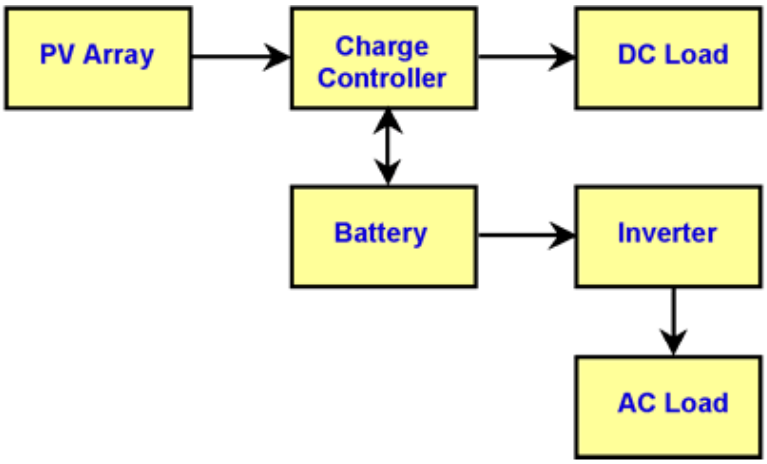

Figure 5. Diagram of stand-alone PV system with battery storage powering DC and AC loads.

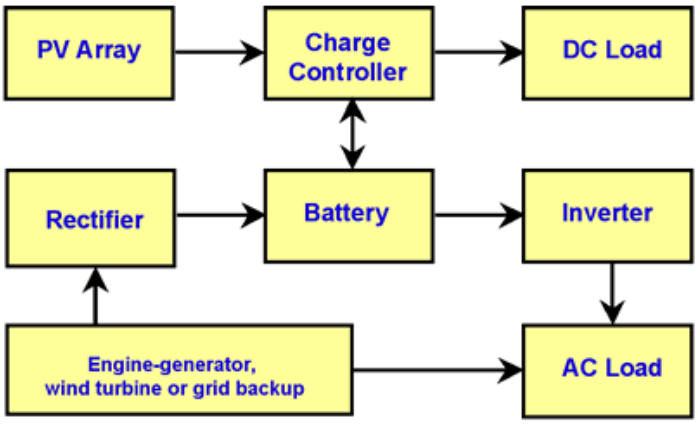

Figure 6. Diagram of photovoltaic hybrid system.

6.3.PV-hybrid systems

Although PV systems will generally have some means of storing energy to accommodate a pre-defined period of **insufficient sunshine**, there may still be exceptional periods of poor weather when an alternative source is required to guarantee power production. **PV-hybrid systems combine a photovoltaic generator with another power sources - typically a diesel generator, but occasionally another renewable supply such as a wing turbine**. **The PV generator would usually be sized to meet the base load demand, with the alternate supply being called into action only when essential**. This arrangement offers all the benefits of PV in respect of low operation and maintenance costs, but additionally ensures a secure supply.

Hybrid systems can also be sensible approach in situations where occasional demand peaks are significantly higher than the base load demand. It makes little sense to size a system to be able to meet demand entirely with PV if, for example, the normal load is only 10% of the peak demand. By the same token, a diesel generator-set sized to meet the peak demand would be operating at inefficient part-load for most of the time. In such a situation a PV-diesel hybrid would be a good compromise.

6.4.Uses of Stand-alone PV power Systems (offgrid)

For many developing countries, where the electricity grid is largely confined to the main urban areas, and where a substantial proportion of the rural population does not have access to most basic energy services, **PV is widely regarded today as the best - and least expensive - means of providing many of the services that are lacking**. Based on minimum energy requirements to provide basic energy services to every individual in the developing world, **the corresponding potential for PV is estimated to be 16 GW (approximately 15 W per capita in the Developing World**).

PV modules can be used for:

- Pumping systems: to supply water to villages, for land irrigation or livestock watering.
- Refrigeration systems: particularly to preserve vaccines, blood and other consumables vital to healthcare programs.
- Lighting: for homes and community buildings such as schools and health centers to enable education and income generation activities to continue after dark.
- Battery charging stations: to recharge batteries, which are used to power appliances ranging from torches and radios to televisions and lights
- Solar home systems: to provide power for domestic lighting and other DC appliances such as TVs, radios, sewing machines, etc.

Agriculture	• water pumping, irrigation • electric fencing for livestock and range management
Community	• water pumping, desalination and purification systems • lighting for schools and other community buildings
Domestic	• lighting, enabling studying, reading, income-producing activities and general increase in living standards • TV, radio, and other small appliances • water pumping
Healthcare	• lighting for wards, operating theatre and staff quarters • medical equipment • refrigeration for vaccines • communications (telephone, radio communications systems) • water pumping • security lighting
Small enterprises	• lighting systems, to extend business hours and increase productivity • power for small equipment, such as sewing machines, freezers, grain grinders, battery charging • lighting and radio in restaurants, stores and other facilities

Table 1.Examples of applications for PV in developing countries

7. Pros and cons of PV

Photovoltaic systems have a number of merits and unique advantages over conventional power-generating technologies. PV systems can be designed for a variety of applications and operational requirements, and can be used for either centralized or distributed power generation. **PV systems have no moving parts, are modular, easily expandable and even transportable in some cases**. **Energy independence and environmental compatibility** are two attractive features of PV systems. **The fuel (sunlight) is free, and no noise or pollution is created from operating PV systems**. In general, PV systems that are well designed and properly installed require **minimal maintenance and have long service lifetimes**.

At present, **the high cost of PV modules and equipment (as compared to conventional energy sources) is the primary limiting factor for the technology**. Consequently, the economic value of PV systems is realized over many years. **In some cases, the surface area requirements for PV arrays may be a limiting factor**. Due to the diffuse nature of sunlight and the existing sunlight to electrical energy conversion efficiencies of photovoltaic devices, surface area requirements for PV array installations are on the order of **8 to 12 m^2** per **KW of installed peak array capacity**.

8.Solar Cells

Solar cells are usually **made from silicon**, the same material used for transistors and integrated circuits. The silicon is treated or "**doped**" so that **when light strikes it electrons are released, so generating an electric current**. There are three basic types of solar cell. **Monocrystalline** cells are cut from a silicon ingot grown from a single large crystal of silicon whilst **polycrystalline** cells are cut from an ingot made up of many smaller crystals. The third type is the **amorphous** or **thin-film** solar cell.

A.Amorphous Solar Cells

Amorphous technology is most often seen **in small solar panels**, such as those in calculators or garden lamps, although amorphous panels are increasingly used in larger applications. They are **made by depositing a thin film of silicon onto a sheet of another material such as steel**. The panel is formed as one piece and the individual cells are not as visible as in other types.

The **efficiency** of amorphous solar panels is **not as high** as those made from individual solar cells, although this has improved over recent years to the point where they can be seen as a practical alternative to panels made with crystalline cells. Their great advantage lies in their **relatively low cost per W of power generated**. This can **be offset, however, by their lower power density**; more panels are needed for the same power output and therefore more space is taken up.

B.Crystalline Solar Cells

Crystalline solar cells are **wired in series to produce solar panels**. As **each cell produces a voltage of between 0.5 and 0.6 Volts**, 36 cells are needed to produce an open-circuit voltage of about 20 Volts. This is sufficient to charge a 12 Volt battery under most conditions.

Although the theoretical efficiency of monocrystalline cells is slightly higher than that of polycrystalline cells, there is little practical difference in performance. Crystalline cells generally **have a longer lifetime than the amorphous variety**.

9. Solar Power Batteries

Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and **to supply it to electrical loads as needed (during the night and periods of cloudy weather)**. Other reasons because batteries are used in PV systems are **to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters**. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and overdischarge.

In stand-alone systems, **the power generated by the solar panels is usually used to charge a lead-acid battery. Other types of battery such as nickel-cadmium batteries may be used, but the advantages of the lead-acid battery ensure that it is still the most popular choice**. ***A battery is composed of individual cells; each cell in a lead-acid battery produces a voltage of about 2 Volts DC, so a 12 Volt battery needs 6 cells. The capacity of a battery is measured in Ampere-hours or Amp-hours (Ah).***

To properly select batteries for use in stand-alone PV systems, it is important that system designers have a good understanding of their design features, performance characteristics and operational requirements. The information in the following sections is intended as a review of basic battery characteristics and terminology as is commonly used in the design and application of batteries in PV systems.

10. Battery Design and Construction

Battery manufacturing is an intensive, heavy industrial process involving the use of hazardous and toxic materials. **Batteries are generally mass produced, combining several sequential and parallel processes to construct a complete battery unit**. After production, initial charge and discharge cycles are conducted on batteries before they are shipped to distributors and consumers.

Manufacturers have variations in the details of their battery construction, but some common construction features can be described for most all batteries. **Some important components** of battery construction are described below.

Cell: The cell is the **basic electrochemical unit** in a battery, consisting of a set of *positive* and *negative plates* divided by *separators*, immersed in an *electrolyte* solution and enclosed in a *case*.

Active Material: The active materials in a battery are the **raw composition materials that form the *positive* and *negative* plates**, and are reactants in the electrochemical *cell*. The amount of active material in a battery is proportional to the *capacity* a battery can deliver. In *lead-acid* batteries, the active materials are *lead dioxide* (PbO 2) in the positive plates and *metallic sponge lead* (Pb) in the negative plates, which react with a *sulfuric acid* (H 2SO4) solution during battery operation.

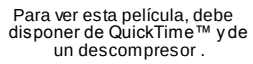

Figure 7:Battery cell composition

Electrolyte: The electrolyte is **a conducting medium** which allows the flow of current through ionic transfer, or the transfer of electrons between the *plates* in a battery. In a lead-acid battery, the electrolyte is a diluted *sulfuric acid* solution, either in liquid (flooded) form, gelled or absorbed in glass mats. In flooded nickel- cadmium cells, the electrolyte is an alkaline solution of potassium hydroxide and water. In most flooded battery types, periodic water additions are required to replenish the electrolyte lost through gassing. When adding water to batteries, it is very important to use distilled or de-mineralized water, as even the impurities in normal tap water can poison the battery and result in premature failure.

Grid: In a lead-acid battery, the grid is typically a lead alloy **framework that supports the *active material* on a battery *plate*, and which also conducts current**. Alloying elements such as *antimony* and *calcium* are often used to strengthen the lead grids, and have characteristic effects on battery performance such as *cycle* performance and *gassing*. Some grids are made by expanding a thin lead alloy sheet into a flat plate web, while others are made of long spines of lead with the active material plated around them forming tubes, or what are referred to as *tubular plates*.

Plate: A plate is a basic battery component, **consisting of a *grid* and *active material,* sometimes called an *electrode***. There are generally a number of *positive* and *negative* plates in each battery *cell*, typically connected in *parallel* at a bus bar or inter-cell connector at the top of the plates. A pasted plate is manufactured by applying a mixture of *lead oxide, sulfuric acid,* fibers and water on to the *grid*. **The thickness of the grid and plate affect the deep cycle performance of a battery**. In automotive starting or SLI type batteries, many thin plates are used per cell. This results in maximum surface area for delivering high currents, but not much thickness and mechanical durability for deep and prolonged discharges. Thick plates are used for deep cycling applications such as for forklifts, golf carts and other electric vehicles. The thick plates permit deep discharges over long periods, while maintaining good adhesion of the active material to the grid, resulting in longer life.

Separator: A separator is **a porous, insulating divider between the *positive* and *negative plates* in a battery, used to keep the plates from coming into electrical contact and short-circuiting**, and which also allows the flow of *electrolyte* and ions between the positive and negative plates. Separators are made from micro-porous rubber, plastic or glass-wool mats. In some cases, the separators may be like an envelope, enclosing the entire plate and preventing shed materials from creating short circuits at the bottom of the plates.

Element: An element is defined as a **stack of positive and negative plate groups and separators, assembled together with plate straps interconnecting the positive and negative plates**.

Terminal Posts: Terminal posts are the **external positive and negative electrical connections to a battery**. A battery is connected in a PV system and to electrical loads at the terminal posts. In a lead-acid battery the posts are generally lead or a lead alloy, or possibly stainless steel or copper-plated steel for greater corrosion resistance. Battery terminals may

require periodic cleaning, particularly for flooded designs. It is also recommended that the clamps or connections to battery terminals be secured occasionally as they may loosen over time.

Cell Vents: **During battery charging, gasses are produced within a battery that may be vented to the atmosphere.** In flooded designs, the loss of electrolyte through gas escape from the cell vents it a normal occurrence, and requires the periodic addition of water to maintain proper electrolyte levels. In sealed, or valve-regulated batteries, the vents are designed with a pressure relief mechanism, remaining closed under normal conditions, but opening during higher than normal battery pressures, often the result of overcharging or high temperature operation. Each cell of a complete battery unit has some type of cell vent.

Case: Commonly made from a hard rubber or plastic, **the case contains the *plates*, *separators* and *electrolyte* in a battery**. The case is typically enclosed, with the exception of inter-cell connectors which attach the plate assembly from one cell to the next, terminal posts, and *vents* or caps which allow *gassing* products to escape and to permit water additions if required. Clear battery cases or containers allow for easy monitoring of electrolyte levels and battery plate condition. For very large or tall batteries, plastic cases are often supported with an external metal or rigid plastic casing.

11. Battery Types and Classifications

Many types and classifications of batteries are manufactured today, each with specific design and performance characteristics suited for particular applications. Each battery type or design has its individual strengths and weaknesses. **In PV systems, *lead-acid* batteries are most common** as we said before, **due to their wide availability in many sizes, low cost and well understood performance characteristics**. In a few critical, **low temperature** applications ***nickel-cadmium*** cells are used, **but** their **high initial cost** limits their use in most PV systems. There is no "perfect battery" and it is the task of the PV system designer to decide which battery type is most appropriate for each application.

In general, electrical storage batteries can be divided into to major categories, *primary* and *secondary* batteries.

11.1. Primary Batteries

Primary batteries can store and deliver electrical energy, but ***can not be recharged***. Typical carbon-zinc and lithium batteries commonly used in consumer electronic devices are primary batteries. Primary batteries **are not used in PV systems** because they can not be recharged.

11.2. Secondary Batteries

A secondary battery can store and deliver electrical energy, and ***can be recharged*** by passing a current through it in an opposite direction to the discharge current. Common ***lead-acid*** batteries used in automobiles and PV systems **are secondary batteries**. Table lists

common secondary battery types and their characteristics which are of importance to PV system designers. A detailed discussion of each battery type follows.

Para ver esta película, debe disponer de QuickTime™ y de un descompresor .

Table 2. Secondary Battery Types and Characteristics

11.2.1.Lead-Acid Battery Classifications

Many types of lead-acid batteries are used in PV systems, each having specific design and performance characteristics. **While there are many variations in the design and performance of lead-acid cells, they are often classified in terms of one of the following three categories**:

a)SLI Batteries

Starting, lighting and ignition (SLI) batteries are a type of lead-acid battery designed primarily for *shallow cycle* service, most often used to power automobile starters. These batteries have a number of thin positive and negative plates per cell, designed to increase the total plate active surface area. **The large number of plates per cell allows the battery to deliver high discharge currents for short periods.** While they are not designed for long life under deep cycle service, SLI batteries are sometimes used for PV systems in developing

countries where they are the only type of battery locally manufactured. Although **not recommended for most PV applications**, SLI batteries may provide up to two years of useful service in small stand-alone PV systems where the *average daily depth of discharge* is limited to 10-20%, and the maximum *allowable depth of discharge* is limited to 40-60%.

b)Motive Power or Traction Batteries

Motive power or traction batteries are a type of lead acid battery **designed for deep discharge cycle service, typically used in electrically operated vehicles** and equipment such as golf carts, fork lifts and floor sweepers. These batteries have a fewer number of plates per cell than SLI batteries, however the plates are much thicker and constructed more durably. High content *lead-antimony grids* are primarily used in motive power batteries to enhance deep cycle performance. Traction or motive power batteries **are very popular for use in PV systems due to their deep cycle capability, long life and durability of design.**

c)Stationary Batteries

Stationary batteries are commonly **used in un-interruptible power supplies (UPS) to provide backup power to computers, telephone equipment and other critical loads or devices**. Stationary batteries may have characteristics similar to both SLI and motive power batteries, but are generally **designed for occasional deep discharge, limited cycle service**.

Battery type (Standard application area)	**SLI** (Cars)	**SLI** (Trucks)	**Lighting/Leisure** (caravans boats cottages)	**Solar** (modified for PV use)	**Semi Traction** (golf carts, lawn mowers etc.)	**Traction** (fork lift trucks i.e.)	**Stationary** (telecom i.e.)
Positive plate design	Pasted	Pasted	Pasted	Pasted	Pasted/ Rod	Tubular	Tubular/ Rod
Advantages	High power	High power			Fairly high power	Accepts deep discharge	Rugged
	Rapid recharge possible	Rapid recharge possible			Acceptable cycle life	Accepts overcharge	Reliable
		Longer PV- life than car battery	Longer PV- life than car battery	Longer PV- life than car battery		Good for cycling application	
Disadvant-ages	Sensitive to deep discharge	Sensitive to deep discharge	Limited cycle life	Limited cycle life	Limited cycle life	Require high overcharge	Sensitive to high overcharge and deep discharge
Relative invest-ment cost (Ref. 2)	1.0-1.3	1.3-1.5	1.5-2	1.4-1.6	1.5-2.0	4-8	4-7
Comments	**Very short life in most PV systems. Not recommended for PV systems**	**Can achieve acceptable lifetime in low cost PV system with shallow cycling**	**Can achieve accept-able lifetime in low cost PV system with shallow cycling**	**Best lifetime in low cost PV systems**	May give favourable life cycle cost in professional PV system with shallow cycles	May give favourable life cycle cost in professional PV system with deep cycles	Plante type is not recommended for PV systems.

Table 3.Battery selection table for PV systems

There are several types of lead-acid batteries manufactured. The following sections describe the types of lead-acid batteries **commonly used in PV systems**.

11.2.1.1.Lead-Antimony Batteries

Lead-antimony batteries are a type of lead-acid battery which **use antimony (Sb) as the primary alloying element with lead in the plate grids.** The use of lead-antimony alloys in

the grids has both advantages and disadvantages. **Advantages** include providing **greater *mechanical strength*** than pure lead grids, and **excellent *deep discharge* and *high discharge rate* performance**. Lead-antimony grids also limit the shedding of active material and have better lifetime than lead-calcium batteries when operated at higher temperatures.

Disadvantages of lead-antimony batteries are a ***high self-discharge rate***, and as the result of necessary overcharge, **require frequent water additions** depending on the temperature and amount of overcharge.

Most lead-antimony batteries are flooded, open vent types with removable caps to permit water additions.

They are **well suited to application in PV systems** due to their deep cycle capability and ability to take abuse, however they do require periodic water additions. The frequency of water additions can be minimized by the use of *catalytic recombination caps* or battery designs with excess electrolyte reservoirs. The health of flooded, open vent lead-antimony batteries can be easily checked by measuring the *specific gravity* of the electrolyte with a *hydrometer*.

Lead-antimony batteries with thick plates and robust design **are generally classified as motive power or traction type batteries**, are widely available and are typically used in electrically operated vehicles where deep cycle long-life performance is required.

11.2.1.2.Lead-Calcium Batteries

Lead-calcium batteries are a type of lead-acid battery which **use calcium (Ca) as the primary alloying element with lead in the plate grids**. Like lead-antimony, the use of lead-calcium alloys in the grids has both advantages and disadvantages. **Advantages** include providing greater ***mechanical strength*** than pure lead grids, a ***low self-discharge rate***, and

reduced gassing **resulting in lower water loss and lower maintenance requirements** than for lead-antimony batteries. **Disadvantages** of lead-calcium batteries include ***poor charge acceptance*** after deep discharges and shortened battery life at higher operating temperatures and if discharged to greater than 25% *depth of discharge* repeatedly.

11.2.1.2.1.Flooded Lead-Calcium, Open Vent

Often **classified as stationary batteries**, these batteries are typically supplied as individual 2 volt cells in capacity ranges up to and over 1000 ampere-hours. Flooded lead-calcium batteries have the **advantages of low self discharge and low water loss**, and may last as long as 20 years in stand-by or float service. **In PV applications, these batteries usually experience short lifetimes due to sulfation and stratification of the electrolyte unless they are charged properly**.

11.2.1.2.2.Flooded Lead-Calcium, Sealed Vent

Primarily developed as 'maintenance free' automotive starting batteries, the capacity for these batteries is typically in the range of 50 to 120 ampere-hours, in a nominal 12 volt unit. Like all lead-calcium designs, they are intolerant of overcharging, high operating temperatures and deep discharge cycles. **They are "maintenance free" in the sense that you do not add water**, but they are also limited by the fact that you can not add water which generally limits their useful life. This battery design incorporates sufficient reserve electrolyte to operate over its typical service life without water additions. These batteries are **often employed in small stand-alone PV systems such as in rural homes and lighting systems**, but must be carefully charged to achieve maximum performance and life. While they are low cost, they are really designed for shallow cycling, and **will generally have a short life in most PV applications**

An example of this type of battery that is widely produced throughout the world is the Delco 2000. It is relatively low cost and suitable for unsophisticated users that might not

properly maintain their battery water level. However, it is really a modified SLI battery, with many thin plates, and will only provide a couple years of useful service in most PV systems.

11.2.1.3.Lead-Antimony/Lead-Calcium Hybrid

These are **typically flooded batteries**, with capacity ratings of over 200 ampere-hours. A common design for this battery type uses *lead-calcium* tubular *positive* electrodes and pasted *lead-antimony negative* plates.

This design **combines the advantages of both lead-calcium and lead-antimony design, including good deep cycle performance, low water loss and long life. *Stratification* and *sulfation* can also be a problem** with these batteries, and must be treated accordingly. These batteries are sometimes **used in PV systems with larger capacity and deep cycle requirements**. A common hybrid battery using tubular plates is the Exide Solar battery line manufactured in the United States.

11.2.1.4.Captive Electrolyte Lead-Acid Batteries

Captive electrolyte batteries are another type of lead-acid battery, and as the name implies, the **electrolyte is *immobilized*** in some manner and the battery is sealed under normal operating conditions. Under excessive overcharge, the normally sealed *vents* open under gas pressure. **Often** captive electrolyte batteries **are referred to as *valve regulated lead acid* (VRLA) batteries**, noting the pressure regulating mechanisms on the cell vents. ***Electrolyte* can not be replenished** in these battery designs, **therefore they are intolerant of excessive overcharge**.

Captive electrolyte lead-acid batteries are **popular for PV applications** because **they are spill proof and easily transported, and they require no water additions making them ideal**

for remote applications were maintenance is infrequent or unavailable. However, **a common failure mode for these batteries in PV systems is excessive overcharge and loss of electrolyte, which is accelerated in warm climates.** For this reason, it is essential that the *battery charge controller* regulation set points are adjusted properly to prevent overcharging.

This battery technology is **very sensitive** to charging methods, regulation voltage and temperature extremes.

Optimal charge regulation voltages for captive electrolyte batteries varies between designs, so it is necessary to follow manufacturers recommendations when available. When no information is available, the charge regulation voltage should be limited to no more than 14.2 volts at 25 C for nominal 12 volt batteries.

A benefit of captive or immobilized electrolyte designs is that **they are less susceptible to freezing compared to flooded batteries**. Typically, lead-calcium grids are used in captive electrolyte batteries to minimize gassing, however some designs use lead-antimony/calcium hybrid grids to gain some of the favorable advantages of lead-antimony batteries.

In the United States, about one half of the small remote PV systems being installed use captive electrolyte, or sealed batteries. **The two most common captive electrolyte batteries are the *gelled* electrolyte and *absorbed glass mat* designs**.

11.2.1.4.1.Gelled Batteries

Initially designed for electronic instruments and consumer devices, gelled lead-acid batteries **typically use lead-calcium grids**. **The electrolyte is 'gelled' by the addition of silicon dioxide to the electrolyte, which is then added to the battery in a warm liquid form and gels as it cools**. Gelled batteries use an internal recombinant process to limit gas escape

from the battery, reducing water loss. Cracks and voids develop within the gelled electrolyte during the first few cycles, providing paths for gas transport between the positive and negative plates, facilitating the recombinant process.

Some gelled batteries have a small amount of *phosphoric acid* added to the electrolyte to improve the deep discharge cycle performance of the battery. The phosphoric acid is similar to the common commercial corrosion inhibitors and metal preservers, and minimizes grid oxidation at low states of charge.

11.2.1.4.2.Absorbed Glass Mat (AGM) Batteries

Another sealed, or valve regulated lead-acid battery, the electrolyte in an AGM battery is absorbed in glass mats which are sandwiched in layers between the plates. However, the electrolyte is not gelled. Similar in other respects to gelled batteries, AGM batteries **are also intolerant to overcharge and high operating temperatures**. Recommended charge regulation methods stated above for gelled batteries also apply to AGMs.

A key feature of AGM batteries is the phenomenon of internal gas recombination. As a charging lead-acid battery nears full state of charge, hydrogen and oxygen gasses are produced by the reactions at the negative and positive plates, respectively. **In a flooded battery, these gasses escape from the battery through the vents, thus requiring periodic water additions. In an AGM battery the excellent ion transport properties of the liquid electrolyte held suspended in the glass mats, the oxygen molecules can migrate from the positive plate and recombine with the slowly evolving hydrogen at the negative plate and form water again**. Under conditions of controlled charging, the pressure relief vents in AGM batteries are designed to remain closed, preventing the release of any gasses and water loss.

11.2.1.5. Calcium-Calcium

The next stage has dominated on a wide front in recent years and is called **Calcium-Calcium**. This involves the antimony on both the negative and positive plates being replaced by calcium alloy. The benefits are obvious. The **fluid loss of the battery is about 80 % lower than that of antimony batteries and the self-discharge is lower**, i.e. they can remain unused for longer periods without losing a lot of their charge. **The disadvantage is that they are more demanding when charging if they have been over-discharged**. **Efforts made in avoiding the gassing had a positive affect, namely that the bubbles moved about in the acid causing it to be thoroughly mixed when charging**. **Without these bubbles the acid can stratify at different densities**, acid weights, and is quite a common phenomenon. An acid weight of 1.35 or more at the bottom and maybe 1.17 at the top when you are looking for an even weight of 1.28 **may cause** the battery **to be affected by sulphating and increased grid corrosion despite the battery being apparently fully charged**.

11.2.2.Lead-Acid Battery Chemistry

Now that the basic components of a battery have been described, **the overall electrochemical operation of a battery can be discussed**. The basic lead-acid battery cell consists of sets positive and negative plates, divided by separators, and immersed in a case with an electrolyte solution. **In a fully charged lead-acid cell, the positive plates are lead dioxide (PbO_2), the negative plates are sponge lead (Pb), and the electrolyte is a diluted sulfuric acid solution. When a battery is connected to an electrical load, current flows from the battery as the active materials are converted to lead sulfate ($PbSO_4$)**.

11.2.2.1.Lead-Acid Cell Reaction

The following equations show the electrochemical reactions for the lead-acid cell. **During battery discharge, the directions of the reactions listed goes from left to right. During battery charging, the direction of the reactions are reversed**, and the reactions go from right to left. Note that the elements as well as charge are balanced on both sides of each equation.

At the positive plate or electrode:

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(Reaction 1& 2)

At the negative plate or electrode:

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(Reaction 3& 4)

Overall lead-acid cell reaction:

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(Reaction 5)

Some consequences of these reactions are interesting and important. As the battery is discharged, the active materials PbO2 and Pb in the positive and negative plates, respectively, combine with the sulfuric acid solution to form PbSO4 and water. **Note that in a fully discharged battery the active materials in both the positive and negative plates are converted to PbSO4, while the sulfuric acid solution is converted to water.**

This dilution of the electrolyte has important consequences in terms of the electrolyte *specific gravity* and freezing point that will be discussed later.

11.2.2.2.Formation

Forming is the process of initial battery *charging* during manufacture. Formation of a lead-acid battery changes the *lead oxide* (PbO) on the *positive plate grids* to *lead dioxide* (PbO 2), and to *metallic sponge lead* (Pb) on the *negative* plates. The extent to which a battery has been formed during manufacture dictates the need for additional cycles in the field to achieve *rated capacity*.

11.2.2.3.Specific Gravity

Specific gravity is defined as the **ratio of the density of a solution to the density of water**, typically measured with a *hydrometer*. By definition, water has a specific gravity of one. In a lead-acid battery, the electrolyte is a diluted solution of sulfuric acid and water. **In a fully charged battery, the electrolyte is approximately 36% sulfuric acid by weight, or 25% by volume, with the remainder water.** The specific gravity of the electrolyte is related to the battery *state of charge*, depending on the design *electrolyte* concentration and *temperature*.

In a fully charged flooded lead-acid battery, the specific gravity of the electrolyte is typically in the range of 1.250 to 1.280 at a temperature of 27 C, meaning that the density of the electrolyte is between 1.25 and 1.28 times that of pure water. **When the battery is discharged**, the hydrogen (H+) and sulfate (SO42-) ions from the sulfuric acid solution combine with the active materials in the positive and negative plates to form lead sulfate (PbSO4), **decreasing the specific gravity of the electrolyte**. As the battery is discharged to greater depths, the sulfuric acid solution becomes diluted until there are no ions left in solution. At this point the battery is **fully discharged**, and the **electrolyte is essentially water with a specific gravity of one.**

Concentrated sulfuric acid has a very low freezing point (less than -50 C) while water has a much higher freezing point of 0 C. This has important implications in that **the freezing point**

of the electrolyte in a lead- acid battery varies with the concentration or specific gravity of the electrolyte. As the battery becomes discharged, the specific gravity decreases resulting in a higher freezing point for the electrolyte.

Lead-acid batteries used in PV systems may be susceptible to freezing in some applications, particularly during cold winters when the batteries may not be fully charged during below average insolation periods.

The PV system designer must carefully consider the temperature extremes of the application along with the anticipated battery state of charge during the winter months to ensure that lead-acid batteries are not subjected to freezing.

11.2.2.3.1.Adjustments to Specific Gravity

In very cold or tropical climates, the specific gravity of the sulfuric acid solution in lead-acid batteries is often adjusted from the typical range of 1.250 to 1.280. In tropical climates where freezing temperatures do not occur, the electrolyte specific gravity may be reduced to between 1.210 and 1.230 in some battery designs.

This **lower concentration electrolyte** will lessen the degradation of the separators and grids and **prolong the battery's useful service life**. **However,** the lower specific gravity **decreases the storage capacity and high discharge rate performance of the battery**. Generally, these factors are offset by the fact that the battery is generally operating at higher than normal temperatures in tropical climates.

In very cold climates, the specific gravity of the electrolyte may be increased above the typical range of 1.250 to 1.280 to values between 1.290 and 1.300. By increasing the electrolyte concentration, the electrochemical activity in the battery is accelerated, improving

the low temperature capacity and lowers the potential for battery freezing. However, these higher specific gravities generally reduce the useful service life of a battery.

While the specific gravity can also be used to estimate the state of charge of a lead-acid battery, **low or inconsistent specific gravity reading between series connected cells in a battery may indicate sulfation,stratification, or lack of equalization between cells**. In some cases a cell with low specific gravity may indicate a cell failure or internal short-circuit within the battery. Measurement of specific gravity can be a valuable aid in the routine maintenance and diagnostics of battery problems in stand-alone PV systems.

11.2.3.Nickel-Cadmium Batteries

Nickel-cadmium (Ni-Cad) batteries are *secondary*, or *rechargeable* batteries, and have **several advantages over lead-acid batteries that make them attractive for use in stand-alone PV systems.** These advantages include ***long life, low maintenance,* survivability from excessive discharges, excellent low temperature *capacity retention,* and *non-critical voltage regulation* requirements**. The **main disadvantages** of nickel- cadmium batteries are their ***high cost* and limited availability** compared to lead-acid designs.

A typical nickel-cadmium cell consists of **positive electrodes made from *nickel-hydroxide* (NiO(OH))and negative electrodes made from *cadmium* (Cd) and immersed in an alkaline *potassium hydroxide* (KOH) electrolyte solution**. When a nickel-cadmium cell is discharged, the nickel hydroxide changes form (Ni(OH)2) and the cadmium becomes cadmium hydroxide (Cd(OH)2). **The concentration of the electrolyte does not change during the reaction so the freezing point stays very low**.

11.2.3.1.Nickel-Cadmium Battery Chemistry

Following are the electrochemical reactions for the flooded nickel-cadmium cell:

At the positive plate or electrode:

$$2NiO(OH) + 2H_2O + 2e^- \Leftrightarrow 2Ni(OH)_2 + 2OH^-$$ *(Reaction 6)*

At the negative plate or electrode:

$$Cd + 2OH^- \Leftrightarrow Cd(OH)_2 + 2e^-$$ *(Reaction 7)*

Overall nickel cadmium cell reaction:

$$Cd + 2NiO(OH) + 2H_2O \Leftrightarrow Cd(OH)_2 + 2Ni(OH)_2$$ *(Reaction 8)*

Notice these reactions are reversible and that the elements and charge are balanced on both sides of the equations. **The discharge reactions occur from left to right, while the charge reactions are reversed**.

The nominal voltage for a nickel-cadmium cell is 1.2 volts, compared to about 2.1 volts for a lead-acid cell, requiring 10 nickel-cadmium cells to be configured in series for a nominal 12 volt battery. **The voltage of a nickel-cadmium cell remains relatively stable until the cell is almost completely discharged, where the voltage drops off dramatically**. Nickel-cadmium batteries are commonly subdivided in to **two primary types**; *sintered plate* and *pocket plate*.

11.2.3.2.Ni-Cd Types:

11.2.3.2.1.Sintered Plate Ni-Cads

Sintered plate nickel cadmium batteries are **commonly used in electrical test equipment and consumer electronic devices**. The batteries are designed by heat processing the active materials and rolling them into metallic case. The electrolyte in sintered plate nickel-cadmium batteries is immobilized, preventing leakage, allowing any orientation for installation. The

main **disadvantage** of sintered plate designs is the so called '**memory effect', in which a battery that is repeatedly discharged to only a percentage of its rated capacity will eventually 'memorize' this cycle pattern, and will limit further discharge resulting in loss of capacity**. In some cases, the 'memory effect' can be erased by conducting special charge and discharge cycles, regaining some of its initial rated capacity.

11.2.3.2.2.Pocket Plate Ni-Cads

Large nickel cadmium batteries used in remote telecommunications systems and other commercial

applications **are typically of a flooded design, called flooded *pocket plate***. Similar to flooded lead-acid designs, these batteries **require periodic water additions, however, the electrolyte is an alkaline solution of potassium hydroxide, instead of a sulfuric acid solution**. **Advantages:**These batteries **can withstand deep discharges and temperature extremes much better than lead-acid batteries, and they do not experience the 'memory effect' associated with sintered plate Ni-Cads**. The main **disadvantage** of pocket plate nickel cadmium batteries is their **high initial cost, however their long lifetimes can result in the lowest life cycle cost battery for some PV applications**.

12. Main Degradation mechanisms of Solar Batteries

In stand-alone PV systems **special attention must be paid to the battery bank**, which is often said to be the weakest component of the system and the **highest contributor to its life cycle cost**. For this reason, designers, project managers are very concerned by the evaluation of the battery lifetime.

The main objective of a cycling test procedure is to evaluate the battery lifetime, expressed in terms of reduced capacity, by reproducing a typical use of the battery in the field. The test procedures induce ageing of the battery by accelerating the degradation (sulphation, corrosion, stratification and softening) of the battery grid and the active mass. The analysis of the results shows that **most of the cycling procedures lead to** significant battery **sulphation,** but **almost none of them accelerate** battery **corrosion**. In fact, there is no test procedure where the four degradation mechanisms lead to a significantly high level of degradation. It is therefore advisable for project managers to select several methods in order to ascertain the most likely battery degradation pattern for a given application and then be able to choose the right battery.

In terms of battery technology, there is a wide range of efficiency and lifetime values for various batteries of the same technology. This is due to differences in the type of grid alloy, the active mass composition, the manufacturing process or the cell geometry. In addition, the **longer and better service of tubular batteries** was confirmed by the analysis.The behaviour of **tubular batteries** is, in general, not very dependent on the selected test procedure, as this kind of battery is more **sensitive to sulphation** than to softening and corrosion. **However, flat**

plate solar batteries are sensitive to all types of degradation and their cycling life is much more dependent on the test procedure.

Nevertheless there is still a lot of work to do on the topic of accelerated battery cycling life evaluation. There is a strong need for a deeper international collaboration to focus on a limited number of cycling procedures, gather more results on battery tests, search for other means to accelerate the tests (key parameters, modelling studies) and lead to the standardization of these cycling tests.

Four main degradation mechanisms can occur in solar battery in operating conditions:

o Softening of the active mass,

o Corrosion of the grid.

o Sulphation,

o Stratification of the electrolyte,

They are briefly described:

12.1.Softening

When a battery is submitted to **successive cycles of charge/discharge, repeated** volume variations of the active mass create some changes in its morphology such as a **modification of the cohesion, the distribution of lead oxides (PbO2) and the size of crystals**. These changes lead to a loose of connection between the aggregates of lead dioxide and a softening of the active mass. The first consequence is a **loss of capacity** caused by a lower participation of this active mass in the electrochemical reactions. The extreme situation is obtained when there is no

more connection between the aggregates and they fall to the bottom of the battery container (see Figure). This process is called shedding.

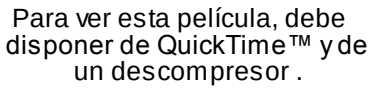


Figure 8. Shedding of the active mass(positive flat plate)

12.2.Corrosion

When a lead-acid battery is in a **high voltage condition (end of charge or overcharge),** the oxygen produced at the positive plate leads to the formation of an oxide layer at the interface between the current collector, or grid, and the active mass (see Figure). A similar corrosion layer is formed **when the battery is left in open circuit conditions for a long time.**

The corrosion layer is resistive which affects the current collection by the grid. There are **many consequences** such as:

o Decrease of electronic exchanges (the layer forms a barrier to ionic diffusion),

o Increase of the internal resistance,

o Decrease of the charge acceptance,

o Decrease of the battery capacity,

o Mechanical consequences,

o Grids becoming thin and fragile.

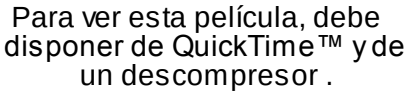
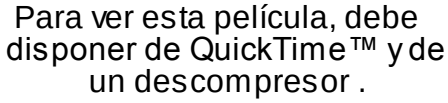


Figure 9.Corrosion Layer (positive collector of a flat plate battery)

12.3.Sulphation

The "so-called" irreversible sulphation phenomenon is the **presence of non-rechargeable lead sulphate crystals in positive and negative active masses**. Lead sulphate is formed **during the discharge** phase of the battery. When the battery remains at low states of charge, a process of re-crystallisation of the lead sulphate crystals happens and affects their characteristics: **PbSO4 crystals at the positive and negative plates become bigger** (see Figures and) **and are less connected with the active mass; thus they are no more rechargeable. This leads to a loss of capacity.**



Figures 10 & 11. On the Left: PbSO4 small crystals. On the right: PbSO4 big crystals

12.4.Stratification

The stratification of the electrolyte is the **presence of a vertical gradient of the concentration of sulphuric acid due to the operation of the battery**. Pure sulphuric acid formed during the charge phase has a higher density than the bulk electrolyte and tends to fall down to the bottom part of the battery. This phenomenon is favoured by **deep discharges and recharges**, but **decreases during overcharge** as the electrolyte is mixed by oxygen and hydrogen gas bubbles. The stratification also depends on the characteristics of the battery such as: the grid alloy (**batteries with lead-antimony grids are less sensitive to stratification**); the plate Grid Corrosion layergeometry (**stratification is favoured with the height of the plates**), and the compression level of the plates stack (**separators slow the descent of acid to the bottom of the battery**). The stratification of the electrolyte leads to a **loss of capacity** (bottom part of the battery less recharged) and to the **forming of irreversible lead sulphate crystals** (see Figure). The stratification phenomenon **does not occur, or only at a low level, in VRLA batteries** because the electrolyte is immobilised in Absorptive Glass Material (AGM) separators or in a gel.

Figure 12. Irreversible lead sulphate crystals due to stratification(positive plates)

This photography is obtained through the use of a radioactive tracer that enables to display the distribution of irreversible lead sulphates at the interface active mass/electrolyte**:** **the lead sulphate crystal density increases from "white" to "red"**, showing here a clear **difference of concentration between the lower and upper parts of the plates**. This methodology has been developed by Genec.

13. Battery Strengths and Weaknesses

Each battery type has design and performance features suited for particular applications. Again, **no one type of battery is ideal for a PV system applications**. **The designer must consider the advantages and disadvantages of different batteries with respect to the requirements of a particular application**. Some of the considerations include lifetime, deep cycle performance, tolerance to high temperatures and overcharge, maintenance and many others. Table 4 summarizes some of the key characteristics of the different battery types discussed in the preceding section.

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Table 4.Batteries Advantages and Disadvantages

14. Battery System Design and Selection Criteria

Battery system design and selection criteria involves many decisions and trade offs. **Choosing the right battery for a PV application depends on many factors.** While no specific battery is appropriate for all PV applications, common sense and a careful review of the battery literature with respect to the particular application needs will help the designer take the decision.

Some decisions on battery selection may be easy to arrive at, such as physical properties, while other decisions will be much more difficult and may involve making tradeoffs between desirable and undesirable battery features. With the proper application of this knowledge, designers should be able to differentiate among battery types and gain some application experience with batteries they are familiar with.Table summarizes some of the considerations in battery selection and design.

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Table 5.Batterie Selection Criteria

15.Life Expectancy of Solar Rechargeable Batteries

Batteries used in solar power systems **can last from one to twenty years, depending on type and how they are used**. Factors such as improper charging and temperature all take their toll on solar batteries.

15.1.Type

Solar batteries are typically deep-cycle, which allows them to discharge up to 80% before recharging. Used properly, they can last several years. Each battery is rated for a certain number of full cycles, i.e. it can be discharged then recharged a certain number of times.

15.2.Typical Lifespan

According to Northern Arizona Wind & Sun, an **AGM deep-cycle battery lasts four to seven years** and a **gelled deep cycle battery lasts two to five years**. **A regular deep cycle battery lasts four to eight years.**

15.3.Industrial Batteries

Less common options are industrial batteries. Premium deep cycle batteries may last 7 to 15 years, industrial type batteries may last 10 to 20 years and surplus telephone (float) batteries can last 2 to 20 years.

15.4.Abuse

The lifespan of batteries can be greatly reduced by abuse. **Lifespan is reduced by storing batteries in temperatures over 77 C**, because they discharge more quickly. **Overcharging is also** an easy way to kill batteries.

15.5.Efficiency

Battery life can be extended by fully discharging them before recharging, i.e using them as designed. Keeping the batteries at a steady temperature, neither overcharging nor excessively draining them, all help.

16. Battery standards

Standards are **produced to facilitate replacement of battery cells** (standardised dimensions and designs) **and the understanding of performance data** (standardised testing methods), etc. The standardisation bodies represent **groups of companies and organisations with a common interest in the production or availability of comparable products** from multiple suppliers or comparable measures of different parameters.

16.1 IEC standards

The International Electrotechnical Committee (IEC) develops and publishes standards for batteries. Several standards are covering the lead-acid battery and its different versions and applications. The most relevant standards are:

- IEC 95 Lead-acid starter batteries
- IEC 254 Lead-acid traction batteries
- IEC 896 Stationary lead-acid batteries
- IEC 1429 Marking of secondary cells and batteries with the international recycling symbol
- IEC 1431 Guide for the use of monitor systems for lead-acid traction batteries.

16.2 Other standards

Other bodies are also developing standards for specific purposes or for geographical regions. It is important to investigate if some standards are valid for your application and put specific demands on the installation at its specific location.

Standards are for example produced by:

- CENELEC produces standards for Europe
- SAE produces standards for the (American) car industry
- DIN produces German national standards
- JISC produces Japanese national standards

17. Safety precautions

The lead-acid battery is an energy pack. It is quite sensitive to abuse. When treated in a wrong way, it is easy to pass over the limits to unstable conditions. ***Never stress the battery mechanically, electrically or thermally beyond the limits.***

17.1 Always use insulated tools

The tools used for connecting batteries have to be insulated to avoid the potential shorting of batteries. Plastic tubes or plastic tape can easily be used for home manufacturing of insulated tools.

17.2 Protect eyes and skin

Safety goggles must always be worn when working with batteries**.**

Rubber gloves should preferably be used to avoid skin contact with the electrolyte**.**

Special clothing is recommended to avoid droplets of acid destroying the normal dress. Such droplets are not always recognised until the clothes are washed and the acid has already made holes in the dress.

Large amounts of water should be used for rinsing if acid has come into contact with the skin, clothes or the construction of the installation. ***It is very important to have a water***

bottle available within easy reach in the working area.

17.3 Protection against explosion

Explosions may result from different abuse situations. An explosion forces the cell case to burst and parts will fly around together with a spray of acid. A fire may also start as a result of the explosion.

The battery should be protected against short circuit by an electrical fuse sized correctly to protect the battery from currents above the maximum load and charge values. The fuse is preferably placed in the middle of the voltage string in the battery pack. The location of the fuse in the middle of the voltage string will be safer if a shortcut only involves some part of the battery. In a small 12V monoblock battery system the fuse should be placed as close as possible to the positive terminal.

When assembling the parts of the installation, ***never connect the battery terminals until all cabling is finished and checked for faults***.

Mechanical abuse may well result in an explosion. Protect the battery from pieces that could fall down on the battery or be injected from the side. Mechanical damage to the battery may result in an explosion, which starts as an internal short circuit when the plates or connectors of different polarity are contacting each other as a result of the damage.

A gas explosion is commonly created by an external spark. When batteries are fully charged and in the gassing mode, the internals of the cells are filled with an explosive gas mixture and gas is issuing through the vents. This gas is highly explosive and a cigarette, a match or even by an electrical spark, can easily ignite it. Such a spark may result from a static discharge when two materials are statically charged or from an electrical circuit.

A gas explosion in one cell will immediately propagate from one cell to all other cells, damaging the whole battery.

17.4 How to carry a battery

Now and then it is necessary to move a battery from one place to another. Since a battery is a heavy piece of equipment it is recommended to **use a special strap which is placed around the terminals**. ***Never try to carry a battery without it.***

First of all this could do severe harm to your back and secondly there is a definitive risk of you dropping the battery on the floor. The result is possible harm to your feet not only from the impact when the battery reaches the floor but also from sulphuric acid if the case breaks.

17.5 Disposal of the battery at end of life

Batteries are considered hazardous items as they contain toxic materials such as lead, acids and plastics which can harm humans and the environment..

For this reason, it is important to reuse the materials for the manufacturing of new batteries.

Such processes for recovery of the metal content of lead-acid batteries are established. If batteries are thrown away, they may leak poisonous metals and acid into the soil.

Under no circumstances should a batteries be disposed of in landfills, or the electrolyte allowed to seep into the ground, or the battery burned.

Be careful to collect old batteries for metal recovery or renovation (mainly in developing countries).They may represent a significant value in some countries.

18. The environmental impacts of batteries

The main objective of this important section is to **know more about the environmental impacts of batteries** .We will see which one has the best environmental profile, we will try to find out if it is really applied on a big scale and what are pros and cons.

Ultimately, we will discuss the environmental impacts of them.

Eight battery technologies are evaluated: lithium-ion (Li-ion), sodium–sulphur (NaS), nickel–cadmium (NiCd), nickel–metal hydride (NiMH), lead–acid (PbA), vanadium-redox (VRB), zinc–bromine (ZnBr) and polysulfide-bromide (PSB).

The energy requirements for production and transport of PV-battery systems that use the different battery technologies differ by up to a factor of three. Production and transport of batteries contribute 24–70% to the energy requirements, and the PV array contributes 26–68%. The contribution from other system components is less than 10%. The contribution of transport to energy requirements is 1–9% for transportation by truck, but may be up to 73% for air transportation. **The energy requirement for battery production and**

transport is dominant for systems based on NiCd, NiMH and PbA batteries.

The **energy requirements for these systems are**, therefore, **sensitive to changes in battery service life and gravimetric energy density**. **For systems with** batteries with relatively **low energy requirement for production and transportation (Li-ion, NaS, VRB, ZnBr, PSB), the battery charge–discharge efficiency has a larger impact.**

Today, lead–acid and nickel–cadmium batteries are commonly used in PV Systems (that is why we have studied only this two kinds of batteries in the "*Section 11.Battery Types and Classifications"*.

Some emerging battery technologies may also be suitable for storage of renewable energy, **such as different types of redox flow batteries and high temperature sodium–sulphur batteries**(the NaS battery is commercially produced and is used in applications for power quality and uninterrupted power supply).

The **PSB, VRB and ZnBr batteries are redox flow batteries based on liquid electrolytes**, which are pumped into the battery stack. The size of the stack determines the power rating, and the volume of the electrolyte determines the storage capacity. **The PSB battery technology has not yet been demonstrated in commercial operation**, and the construction of two plants with a power rating of 12–15 MW and an energy capacity of 120 MWh was stopped in 2003 . The VRB battery technology has been demonstrated by different manufacturers for load levelling and PV applications with power ratings up to 1.5 MW and an energy capacity up to 5 MWh.

Demonstration units of the ZnBr battery have been built for PV applications with the ratings of 50 kW/100 kW h and 250 kW/500 kW h.

There are also included **NiMH and Li-ion batteries** since **their use in small scale applications is growing rapidly**. **However, their relatively high production cost has**

precluded them from employment in applications for storage of several hundreds of kiloWatt hour.

Identification of the important parameters in PV applications can be used to direct research and product improvements, and comparison of different battery technologies can be used to guide battery choice for specific user conditions.

For energy technologies, the energy requirement for producing equipment is an important performance parameter. Large energy requirements in comparison to energy output will limit the range of possible applications to small niches. Energy requirements for producing PV modules have been studied and debated since the early 1970s, while batteries have gained less attention.

In a study of solar home systems, it was concluded that **lead–acid batteries contribute significantly to the energy requirements**.

The purpose of this study is to provide an energy analysis to **enable comparison of different battery technologies in renewable energy applications. By quantifying energy efficiencies and the energy requirements for manufacturing the different systems**, increased awareness may lead to improved energy management of energy storage systems.

The battery parameters investigated are battery charge–discharge efficiency, service life, gravimetric energy density and energy requirements for production and transport of the batteries .

In Table 6 we can see some characteristics of the different kinds of batteries that we will study(not only the two types that we studied before).

Technology	Abbreviation	Model	Description	Positive electrode or catholyte	Electrolyte	Negative electrode or anolyte
Li-ion	Li-ion	SAFT Li-ion VL 50 E Mixed oxide: LiNi0.8(Co+M) 0.2 O_2[a]	Cylindrical, sealed maintenance free cells	$Li_{1-x}MeO_2$/ $LiMeO_2$[a]	PC, $LiPF_6$	Li_xC/C
Sodium–sulphur	NaS	NGK-TEPCO E50 module, 50 kW, 430 kWh/module	384 T5 cells (8 serial × 6 parallel) × 8 serial, 128 V	xS/S_x^{2-} ($x = 5 - 3$)	β-Al_2O_3	Na/Na^+
Nickel–cadmium	NiCd	SAFT Sunica.plus 1110	Pocket plate, thick electrodes, felt-isolated, vented, flooded electrolyte	$NiOOH/Ni(OH)_2$	20% KOH (1.2 kg/dm^3)	$Cd/Cd(OH)_2$
Nickel–metal hydride	NiMH	SAFT NH12.3, 12 V module	EV battery plates, foam electrodes, sealed maintenance free	$NiOOH/Ni(OH)_2$	KOH	MmH/Mm[b]
Lead–acid	PbA	Tudor Exide 16OGi 1260	Vented, pasted flat plates, flooded electrolyte[c]	$PbO_2/PbSO_4$	1.3 kg/dm^3 H_2SO_4	$Pb/PbSO_4$
Polysulfide-bromide	PSB	Regenesys	Redox flow	$NaBr_3$(aq)/ 3 NaBr(aq)	H_2SO_4	2 Na_2S_2(aq)/ Na_2S_4(aq)
Vanadium	VRB	Sumitomo Electric Industries	Redox flow, 4 stacks × 80 cells (serial)	VO_2^+(aq)/VO^{2+}(aq)	1.8 M V in 4.2 M H_2SO_4	V^{2+}(aq)/ V^{3+}(aq)
Zinc–bromine	ZnBr	ZBB research	Redox flow	Br_2(aq)/2 Br^-(aq)	2.25 M $ZnBr_2$	Zn/Zn^{2+}(aq)

Table 6.Description of the batteries used in the PV-battery system

The PV modules are assumed to be based on multi-crystalline silicon (mc-Si), i.e. the PV technology that currently dominates the market

Table 7 shows that the energy efficiencies were estimated to be 0.12–0.13 for the PV modules, 0.90–0.95 for the charge regulator and 0.92–0.94 for the inverter. **Corrections for power or temperature deviation, incomplete utilisation of irradiation etc. are not explicitly considered** for these components but are assumed to be included in these efficiency ranges.

The charge–discharge efficiency is highest for the Li-ion battery and lowest for the PSB battery.**For batteries requiring pumps and auxiliary components, these losses are included**.

The annual solar irradiation (H) was assumed to be 1.7 MWh/m2 yr, representing medium irradiation levels, which can be found in Southern Europe and large parts of the USA . **The maximum solar irradiance (Sp) is assumed to be 1000 W/m2**.

Components	η_i	α_S
1 PV (mc-Si)	0.12–0.13	
2 Charge regulator	0.90–0.95	
3 Batteries[a]		
Li-ion	0.85–0.95	
NaS[b]	0.75–0.83	
PbA	0.70–0.84	
NiCd	0.65–0.85	
NiMH	0.65–0.85	
VRB[c]	0.60–0.80	
ZnBr[d]	0.60–0.73	
PSB[d]	0.60–0.65	
4 Inverter	0.92–0.94	
5 Air conditioning		3

Table 7 Energy efficiencies of the PV-battery system components

18.1. Service life of the components

The end of battery service life is when the battery capacity has reached 80% of its initial capacity or when it fails to function. The **effects of ambient temperature on the performance and service life of redox flow batteries and the NaS battery are limited** since their operating temperatures are regulated by pumping of the electrolytes or by thermal management systems.

When Li-ion, NiCd, NiMH and PbA batteries are used in applications with **shallow cycling, their service life normally will be limited by float life**.

In systems where the cycling is deep, but occurs only a few times a year, temperature dependent corrosion processes is the normal life limiting factor, even for batteries with low cycle life.

In systems with deep daily cycling, the cycle life determines the service life of the battery.

Table 8 shows that **NiCd and VRB batteries have the highest float service life while PSB, Li-ion, VRB and NaS have the highest cycle life at 33% DOD(depth of discharge). Considering life limiting conditions, the VRB, Li-ion and NaS have the highest service lives.**

Component	t_l (yrs)	N_{100}[a] (1000 × cycles)	N_{80}[b] (1000 × cycles)	N_{53}[c] (1000 × cycles)	$t_{3,cycle}$[d] (yrs)	$t_{3,float}$[e] (yrs)	$t_{3,limit}$[f] (yrs)
1 PV array (mc-Si)	30						
2 Charge regulator	10						
3 Batteries							
VRB[g]		2.8–3.0	3.0–4.0	7.0–8.0	19–22	15–20	15–20[h]
Li-ion		3.0–5.0	5.0–7.0	7.0–10	19–27[i]	14–16	14–16[h]
NaS		2.3–2.5	4.5–5.0	6.8–7.5	19–21	14–16	14–16[h]
NiCd		0.3–0.5	1.0–1.5	4.8–6.0	13–16	20–25	13–16
PSB[j]		9.0–10	9.0–10	9.0–10	25–27	14–15	14–15[h]
ZnBr		1.5–2.5	2.5–3.0	4.0–5.0	11–14	8.0–10	8.0–10[h]
NiMH		0.60–1.0	0.80–1.2	2.8–3.0	7.7–8.2	8.0–10	7.7–8.2
PbA[k]		0.32–0.80	0.40–1.0	0.90–2.0	2.5–5.5	8.0–12	2.5–5.5
4 Inverter	10						
5 Air conditioning	8						

Table 8.Service life of PV-battery system components

As the temperature increases, the electrochemical activity of the battery increases as well as the speed of the natural ageing of the active material. Accelerated life tests at elevated temperature, correlated with corrosion studies, provide a basis for estimating service life. **Service temperature is the key factor in determining corrosion**. **As a rule, for PbA batteries every 10 °C increase in temperature reduces service life by 50%** . Valve regulated lead-acid batteries have been shown to have >15 years float service life at 20 °C and >10 years at 25 °C . **The rate of ageing for NiCd batteries is about 20% reduction in life for 10 °C increase in temperature** . **NiCd is less affected than PbA since increased electrochemical activity has little effect on the steel structural components of the NiCd electrode assembly**.

The PSB and VRB batteries are little affected by varying ambient temperatures, since pumps are used to circulate the electrolyte to heat exchangers, which maintain their operating temperatures.

No degradation of the NaS battery has been documented, but the temperature of the electronic control systems has to be controlled. Elevated temperature may degrade the plastic materials of the ZnBr battery, but no degradation has been quantified.

18.2. Energy requirements for production and transport of the PV-battery system components

The gravimetric density for the PV array, including module frame, was estimated at 9 kg/m2 for roof integrated systems and 12 kg/m2 for ground mounted systems. Table 9 shows that the mass of the PV array is 2.6–4.9 tons depending on the energy efficiency of the battery technology used. **The PSB and VRB are the heaviest** ones (24–49 tons) followed by PbA (15–24 tons). The mass of these systems is 5–8 times higher than that of the **Li-ion battery, which has the lowest weight.** The weight fraction of the electrolyte active material, y, is 0.32–0.40 for the redox flow batteries (PSB, VRB and ZnBr) and 0 for the other batteries.

Component	w (kg/m^2)	v_i (kg/kW$_{el}$)	d (Wh/kg)	mass, m_i[a] (tons)
1 PV array (mc-Si)	9.0[b]			2.6–4.9
2 Charge regulator		10		0.56–0.91
3 Batteries				
NaS			103–116	4.1–4.8
Li-ion			80–120	4.0–6.1
ZnBr			70–85	5.6–7.0
NiMH			35–55	8.7–14
NiCd			22–30	16–22
PbA			20–32	15–24
VRB			15–20	24–33
PSB			10–15	32–49
4 Inverter		10		0.50
5 Air conditioning		42[c]		0.086–0.50

Table 9.Service life of PV-battery system components

The energy requirements for mc-Si modules are estimated at 4200 MJ/m2 or 32 MJ/W.

The energy requirements for production of single crystalline silicon (sc-Si) and amorphous silicon (a-Si) modules are 16–20% higher and 0–17% lower, respectively, than that for mc-Si.

Module frames are assumed to use 2.5 kg Al/m2 module corresponding to 500 MJ/m2 .

Energy requirements for array supports in roof integrated and ground mounted systems have been estimated to be 700 MJ/m2 and 1800 MJ/m2, respectively . The total energy requirements for production of PV arrays (module, frame and array support) were calculated to be 5400 MJ/m2 (roof integrated) and 6500 MJ/m2 (ground mounted), corresponding to 45–54 MJ/W.

Energy requirements for producing the inverter, charger and AC were estimated to be 1 MJ/ W, resulting in 70–100 MJ/kg (Table 11).

Energy requirements for production of batteries were assessed from cradle to gate, including materials production and battery manufacturing. To enable a thorough evaluation of different LCA studies, it is needed to report the following parameters:

(1) battery mass, (2) battery capacity, (3)choice of system boundaries (geographical, temporal, technological), (4) electricity´s share of gross primary energy requirements, assumed efficiency of electricity production and method for adding up different energy qualities, (5) recycling rate of used batteries, (6) energy requirements for battery manufacturing processes and production of virgin and recycled materials, respectively, (8) battery design, (9) battery material composition and (10) the allocation principles for multi- output processes.

Based on published life cycle assessments and estimates , the energy requirements for production of different batteries were estimated. The energy requirements for battery production were scattered between studies, and there are uncertainties on the material requirements and manufacturing processes, particularly for the Li-ion, NaS and all the redox flow batteries. The best estimates are presented in Table 10.

The energy requirements of batteries with active materials in solid phase are assumed to be independent of the required PV-battery system output power by changing the cell configuration and voltage of the battery strings.

The energy requirements for production of batteries range from 0.87 MJ/Wh (PbA

based on recycled materials) to 4.1 MJ/Wh (NiCd based on virgin materials) (Table 10). **Differences are partly explained by the energy intensity of materials production.** For the NiCd battery, steel and nickel contribute 60–70% to the energy requirements of materials production. Production of nickel requires 2–8 times more energy than that for the lead used in PbA batteries.

The energy requirements for manufacturing processes contribute 33–78% of the energy requirements for battery production, resulting in relatively small changes between virgin and recycled materials.

The energy requirements for battery manufacturing are assumed to be constant while the energy requirements for materials vary depending on the recycling of materials. **The production of recycled materials requires 32–75% less energy than virgin materials since the energy for extraction from mines and reduction of metals are allocated to the first material life cycle** (Table 10). For redox flow batteries, it is assumed that the energy requirements for production of stack and other battery components are the same as for electrolyte production.

At the end of the service life of redox flow batteries, they can be renovated by renewing the stacks while the electrolyte with active material is assumed to be used indefinitely. Batteries based on active materials in solid phase (Li-ion, NaS, NiCd, NiMH, PbA) need to be manufactured and replaced completely.

Component	Materials and manufacturing (MJ_{pf}/m^2)	Materials and manufacturing (MJ_{pf}/W_{el})	Recycled materials production (MJ_{pf}/Wh)	Virgin materials production (MJ_{pf}/Wh)	Manufacturing (MJ_{pf}/Wh)
1 PV array (mc-Si)	5400[a]				
2 Charge regulator		1.0[b]			
3 Batteries					
Li-ion			0.31	0.67	1.2
NaS			0.29	0.80	0.60
NiCd			1.0	2.0	2.1
NiMH			0.60	1.6	2.1
PbA			0.45	0.77	0.42
PSB[c]			1.1	1.7	0.59
VRB[c]			1.4	2.1	0.74
ZnBr[c]			0.30	1.2	0.60
4 Inverter[b]		1.0[b]			
5 Air conditioning		1.0[d]			

Table 10.Energy requirements for production of the PV-battery system components

Component	Materials and production, $q_{P,i}$ (MJ_{pe}/kg)	Recycled materials production, q_{RR3} (MJ_{pe}/kg)	Virgin materials production, q_{RV3} (MJ_{pe}/kg)	Manufacturing, q_{M3} (MJ_{pe}/kg)	β_i[a]
1 PV array (mc-Si)[b]	600				
2 Charge regulator	100				0.50
3 Batteries					
Li-ion		25–37	53–80	96–144	0.75
NaS		30–34	82–93	62–70	0.70
NiCd		22–30	44–60	46–63	0.68
NiMH		21–40	54–102	74–139	0.68
PbA		9.0–14	15–25	8.4–13	0.65
PSB		11–17	17–26	5.9–8.9	0.50
VRB		21–29	32–42	11–15	0.41
ZnBr		21–26	84–102	42–51	0.50
4 Inverter	100				0.50
5 Air conditioning	70				0.50

Table 11.Energy requirements for production of the PV-battery system components expressed per kilogram component

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18.3.Contributing components

Production and transportation of batteries contributes 24–70% of the energy requirements of the PV-battery system. The relative contribution from the production of batteries is lowest for the ZnBr battery and highest for the NiMH battery.

The contribution of production and transport of the PV array is 26–68% (NiMH–ZnBr). The highest absolute energy requirement for PV array production is 88–96 GJ/yr for the redox flow batteries due to their relatively low efficiency, resulting in the need for a larger PV array and charge regulator. **Production and transport of the charge regulator and inverter contribute 2–4%, respectively**.

The contribution of transport of all the components to the gross energy requirement is low (0.9–8.9%) for 3000 km transport by heavy truck. The **lowest energy requirement for transport is for the ZnBr battery** due to its high energy density and the possibility of recycling the electrolyte. **The transport of PbA batteries contributes 8.9% to the gross energy requirement since these batteries have a relatively low energy density and cycle life, and therefore a larger mass of batteries has to be transported.**

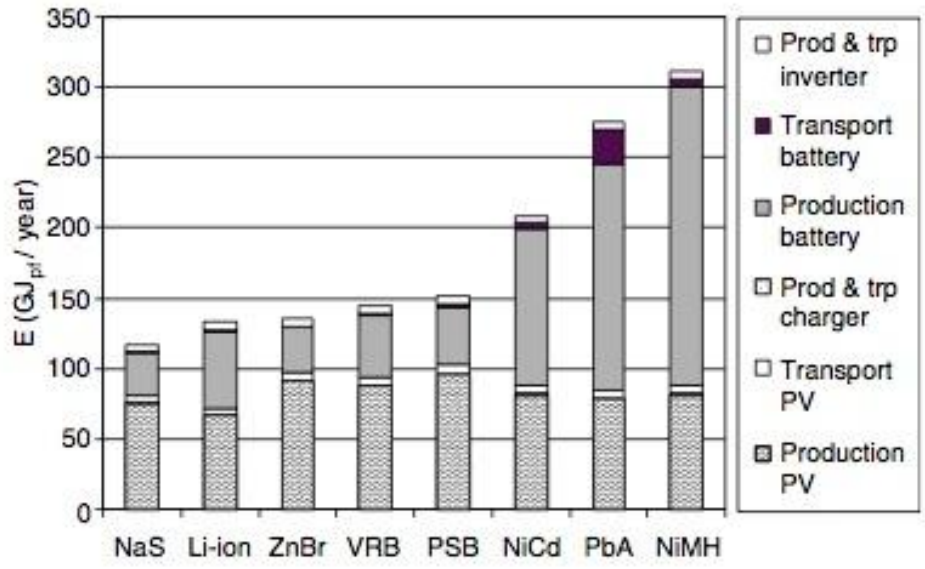


Fig. 13. Energy requirements for production and transport of various PV-battery Systems in a base case

18.4. Influence of different user conditions

The influence of different user conditions was evaluated by calculating the energy requirements for different cases as shown in Table 12. Table 13 provides a summary of the energy requirements for the different cases.

The effects of temperature on the energy requirements of the PV-battery system are shown in Fig. 14. **To cool the battery with an air conditioning unit when the ambient temperature is high the energy requirements increase 2–17% compared with the base case**.

The consequences of recycling of battery materials is analysed in Fig. 14. **When not using materials from recycled production, the energy requirement** increases 17– 75 GJ/yr, which **is 10–53% higher** than if materials of recycled origin are used. **The difference between virgin and recycled materials production is greatest for the ZnBr battery**.

We can also see in Fig 14 that **the energy intensity for plane transportation is 28 times higher than that for truck transportation**. ZnBr is least affected by plane transport due to its

long service life and high energy density.

The results show that for certain battery technologies and conditions, batteries contribute significantly to the total energy requirement for production of PV-battery systems.

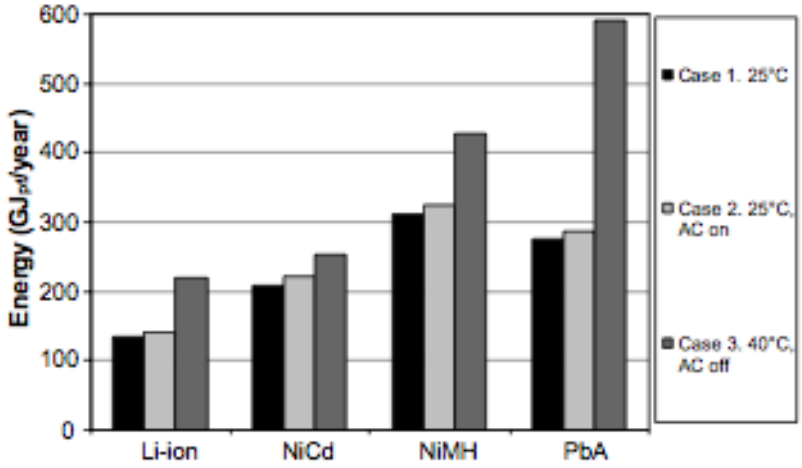


Fig. 14. Energy requirements for production and transport of PV-battery systems at different operating temperatures.

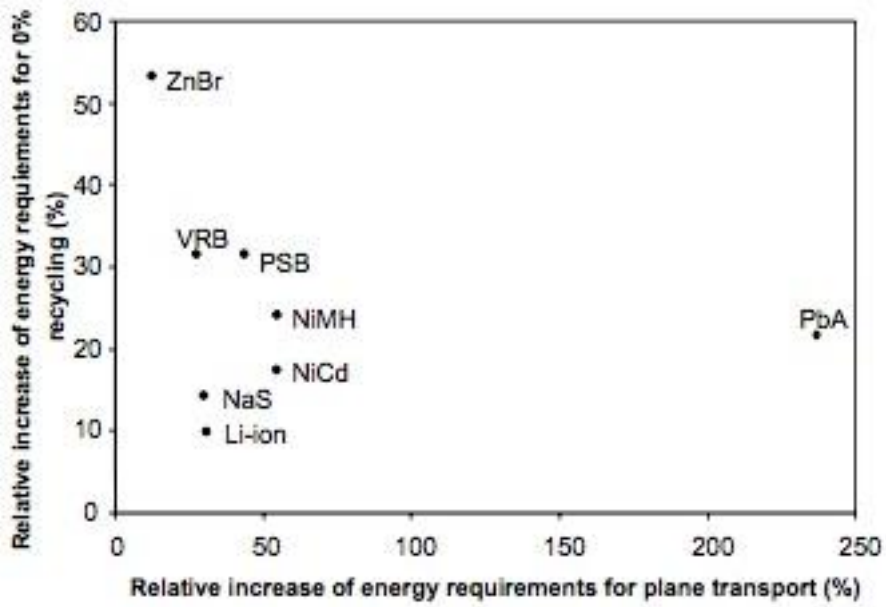


Fig. 15. Changes of energy requirements relative to Case 1 for different recycling rates and modes of transportation

18.5. Uncertainties

The low and high values indicate the uncertainties in the data as well as the improvement potential of different technologies. Input data with large impact and large uncertainty interval is

the battery charge–discharge efficiency and the battery service life. The uncertainty in output results for different battery technologies vary between 8% and 61%. The difference between low and high values of input data is 1.1–2.2 times, where the highest variability is for NiMH and PbA. **Since all battery technologies, except for PbA and NiCd, are immature for PV applications, there are uncertainties about their performance**.

Only a small number of demonstration units have been built of VRB, PSB, ZnBr and NaS batteries, and mass production is likely to improve the production efficiency of these batteries. **Energy requirements for production of batteries may vary considerably depending on material requirements and where and how they are manufactured. Uncertainties are due to restricted availability of information since companies manufacturing batteries protect their technology from competitors**. **Material requirements for immature technologies can change fast in the course of development.**

18.6. Future research

Data on energy requirements for production of batteries come from different sources, which make comparisons unreliable because the system boundaries may be inconsistent. Further work is, therefore, **needed to improve the data quality on material and energy requirements of batteries.**

For the redox flow batteries, energy requirements need to be expressed for power and storage capacity, respectively, in order to enable evaluation of the potential benefits of independent sizing of power and capacity of redox flow batteries. **The influence of temperature on battery service life has to be further analysed**. The effects of different battery charge–discharge efficiencies on the battery temperature and cooling requirements have to be further investigated. The energy model of this study can be further developed with functions for assessing the influence of the rate of battery self-discharge. The model can be

extended to include assessment of resource use, emissions and potential environmental impact of different technologies. **Flywheels, fuel cells with hydrogen storage in PV systems may be evaluated and compared with batteries**.

18.7. Energy return factor

Fig. 16 shows that the energy return factor for the PV-battery system ranges from 2.2 for NiMH batteries (low estimate) to 10 for Li-ion batteries (high estimate). **The NaS battery has the highest average energy return factor (8.5), which means that the PV–NaS battery system will replace 8.5 times more energy throughout its lifetime than the energy required for its production.**

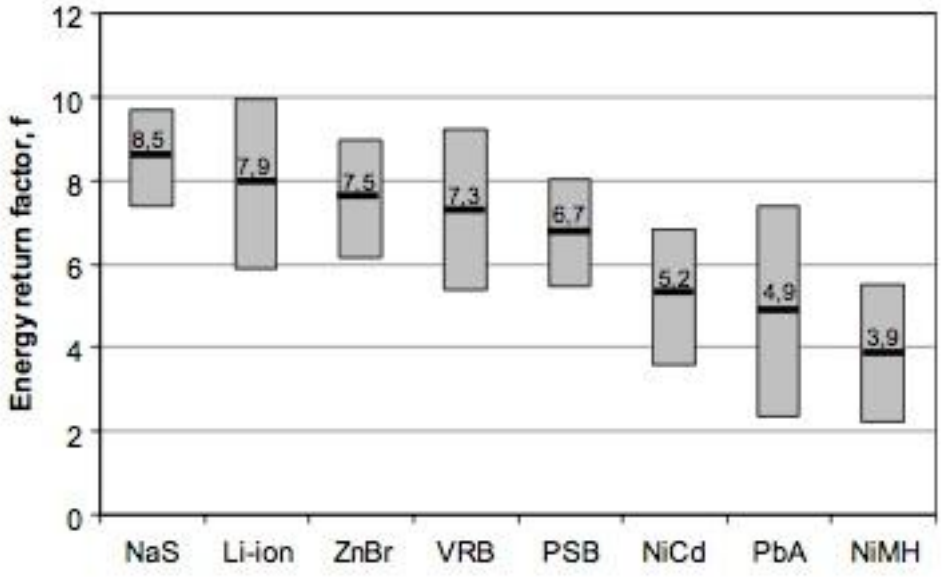


Fig. 16. Energy return factors for the PV-battery systems

The **uncertainty intervals of many batteries are overlapping** (Fig. 15). This shows the importance of using case-specific data when comparing different battery technologies. The **greatest uncertainty is found for systems with a PbA battery due to the high variability in lifetime and energy requirements**. The low estimate of the energy return factor for PbA (using air transport) is as low as 0.68. If the operating temperature at the same time is increased to 40 °C and no material is recycled , then the energy return factor is 0.25. In this extreme case, four times more primary fossil energy is needed to produce and transport the system than what is replaced.

As we said before,production and transportation of batteries contributes 24–70% to the total indirect energy use of the PV-battery system compared to 26–68% for the PV array.**Given a system lifetime of 30 years, the PV array contributes 1.8–3.3 yr and batteries 0.72–10 yr to the energy payback time depending on the technology, showing the energy related significance of batteries in PV- battery systems.**

The importance of energy requirements for battery production increases in relation to PV at locations with high irradiation and vice versa. At locations with low irradiation

levels, the power rating of the PV arrays has to be increased to produce the same amount of electricity. This results in higher indirect energy requirements for production of PV arrays. The importance of the level of solar irradiation for the total energy return factor depends on the relative contribution of the PV array to the indirect energy requirements of the PV-battery system. **An increase of the solar irradiation by 30% increases the energy return factor of the PV- battery system by 9–20%**.

The energy return factor is very sensitive to assumptions about the conversion efficiency of the electricity generation technology the PV system replaces.A conversion efficiency of 0.20 was selected as a default value to represent a Diesel generator since it is likely that a PV-battery system can replace its use in an off grid application. If the efficiency of the Diesel generator is 0.25, the energy return factor is reduced by 20% (1-0.20/0.25). Assuming that the PV-battery system replaces a grid connected system where the electricity conversion efficiency is 0.35, the energy return factor decreases by 43%.

18.8. The overall battery efficiency

The direct efficiency of the battery system (charger, battery and inverter) is 0.50–0.85. **Adding the indirect energy requirement results in overall efficiencies from 0.41 for the NiMH battery (low estimate) to 0.80 for the Li-ion battery (high estimate)** (Fig. 17).

Fig. 18 shows how the gross electricity requirement is used. The energy requirements for production and transport of the charger, the battery and the inverter have been converted to electricity. **Energy losses in the batteries are significant and vary from 9% for the Li-ion battery to 27–33% for the redox flow batteries**. Losses in the charger and inverter are 6–8% and 4–5% of the gross energy requirement, respectively. **Production and transport of the charger and inverter contribute less than 1% of the gross energy requirement, while production and transport of batteries contribute 11–19% for NiCd, PbA and NiMH**.

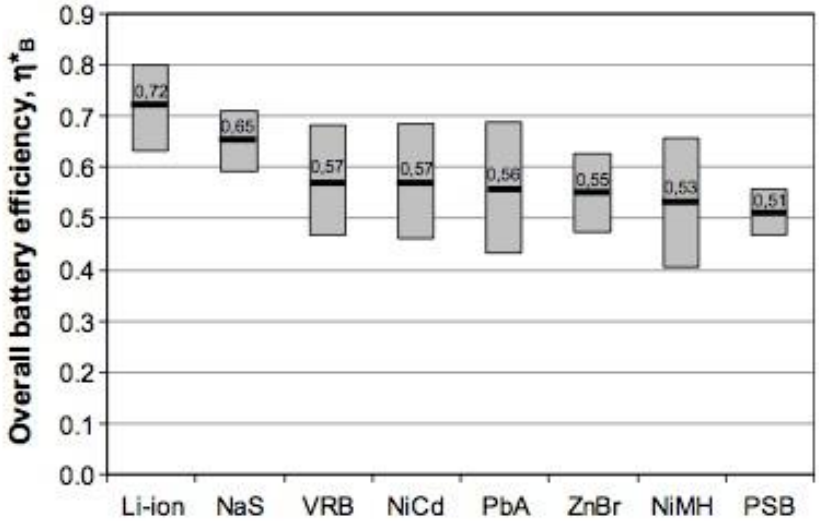


Fig. 17. Overall battery efficiencies including production and transport of charger, battery and invertir

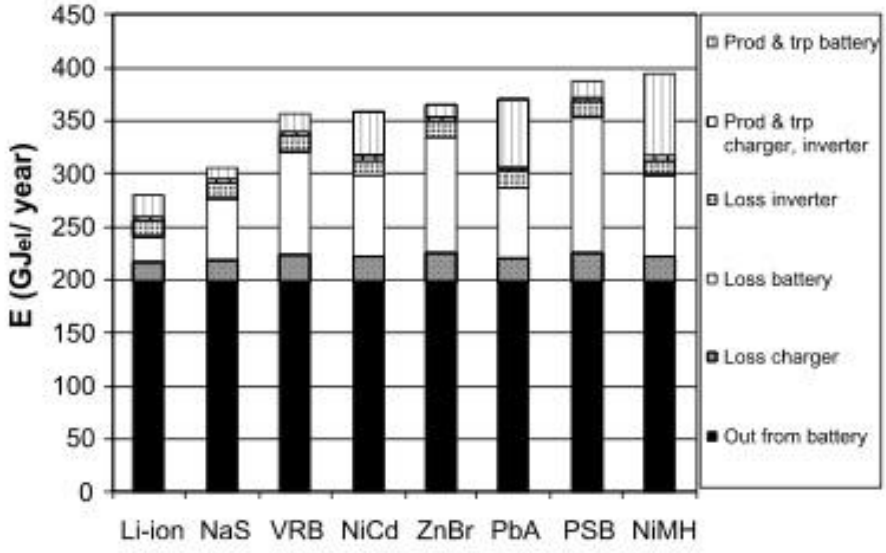


Fig. 18. Gross electricity requirements for charger, battery and inverter including their production and transport

18.9. Different efficiency measures and battery design

To increase energy efficiency, the technical performance of batteries may be improved. **The relative importance of different battery parameters for energy efficiency was, therefore, analysed** including service life , charge–discharge efficiency and energy requirements for production . **For all batteries, the overall battery efficiency is most**

sensitive to changes of the charge-discharge efficiency . Changes in the efficiency of the Li-ion battery have a relatively small influence compared with the other battery technologies. This is because the losses in the Li-ion battery correspond to only 9% of the gross energy requirement, compared with 18–33% for the other Technologies.

Improvement in the charge–discharge efficiency is also most important for the energy return factor of Li-ion, NaS, PSB, VRB and ZnBr batteries. Since losses in the battery must be compensated by higher energy input, **low battery efficiency results in a larger PV array and charger, which means higher indirect energy requirements**.

The service life (and energy density) affects both energy requirements for production and transport. Short battery service life means that batteries have to be replaced more often, resulting in higher energy requirements for battery production and transport. **The low energy density and short service life of PbA results in a larger share of transportation energy**.

18.10.Uncertainties

The low and high values indicate the uncertainties in the results as well as the improvement potential of different technologies. Input data with high influence and large uncertainty interval is the battery charge–discharge efficiency and the battery service life. **The uncertainty in output results for different battery technologies vary between 8% and 61%.** The difference between low and high values of input data is 1.1–2.2 times, where the highest variability is for NiMH and PbA.

Since all battery technologies, except for PbA and NiCd, are immature for PV applications, the stated uncertainties for the other batteries could be underestimated.

The performance ratio, which is the ratio between the final yield and the reference

yield of a PV system, is a common indicator for expressing the efficiency from PV array to useful energy.

It was calculated calculated the energy payback time for PbA batteries in a solar home system (SHS) to be 10–19 yr. The number of days of autonomy that was used for this calculation was 6.8–20 days (battery voltage 12 V, battery capacity 70–100 A h and array output 60–124 W h/day). Recalculated to 3 days of autonomy, the energy payback time for the battery is 1.5–8.4 yr.. The service life for the starting- lighting-ignition (SLI) battery is assumed to be 3 yr. In SHS, without charge regulator and poor battery maintenance, the service life may be less than 3 yr when standard SLI- PbA batteries are used.

Improvement of the charge/discharge strategy can extend the service life of PbA batteries in PV applications .

19. Conclusions

The first thing that we can see is that the only two kinds of batteries that are applied nowadays on a big scale are Lead Acid Batteries(in a lot of different ways) and Ni-Cd Batteries.

That´s why we have studied in more detail this two kinds of batteries.

In my opinion, government should have an effort to promote the use of more Ni-Cd instead of Lead Acid Batteries,because they have some high advantages,such as ***long life, low maintenance,*** **survivability from excessive discharges, excellent low temperature** ***capacity retention,*** **and** ***non-critical voltage regulation*** **requirements**. The **main disadvantages** of nickel-cadmium batteries are their ***high cost*** **and limited availability** compared to lead-acid designs,and that´s why governments should make an effort in this aspect .

However there are a lot of other new and "under study" kind of batteries that would have much higer efficiencies and, therefore,less environmental impact, such as NaS or Li-ion, but it is not proved its application at big scale, and more studies about their performance are needed.

We could observe in the Energetic study of all the kinds of batteries that:

The energy requirements for production of the PV-battery system differ up to a factor of three for the different battery technologies. Production and transport of batteries contribute 24–70% to the energy requirements. The contribution of production and transport of the PV array is 26–68%, depending on the battery technology used. The contribution of transport to the indirect gross energy requirements is 1–9% (with 3000 km transportation by heavy truck).

To reduce the energy requirements of producing and transporting battery systems, the development of battery technologies should aim at higher charge–discharge efficiencies and more efficient production and transport of batteries. **The battery charge–discharge efficiency has a high influence on the system energy requirements for batteries with relatively low**

energy requirements for production and transportation (Li-ion, NaS, VRB, ZnBr, PSB). **Service life, gravimetric energy density and battery production processes are of greater importance for NiCd, NiMH and PbA batteries**. The data on energy requirements for production and transport can be used to calculate the energy return factors and overall battery efficiencies of PV-battery Systems.

If we talk now about Energy return factors and overall battery efficiencies, we can see that:

With a battery energy storage capacity three times higher than the daily energy output, the energy return factor for the PV-battery system ranges from 2.2 to 10 in a reference case. **In extreme cases, energy return factors below one occur, implying no net energy output.**

The energy payback time is 1.8–3.3 yr for the PV array and 0.72–10 yr for the battery, showing the energy related significance of batteries and the large variation between different technologies.

The direct **energy efficiency of the battery system** (charger, battery and inverter**) is 0.50–0.85.**

When considering the overall battery efficiency for the energy exchange assumption, including the production and transport of charger, battery and inverter, the values are 0.41 and 0.80 for the different battery technologies.

The overall battery efficiency is most sensitive to changes of the **charge–discharge efficiency. For batteries with relatively low energy requirements for production and transportation (Li-ion, NaS, VRB, ZnBr, PSB), this parameter is also most important for the energy return factor**.

Not only the ranking order of battery parameters but also **the ranking order of batteries in terms of energy efficiency** and the optimal system design and operation (e.g. the use of AC)

are in many cases dependent on the type of energy efficiency measure that is used .For any analysis, it is important to characterise and be clear about the context with regard to operating conditions, what resource use should be minimised, alternative technologies and the character of the general energy system.

20. Annex. Lead Acid Battery Recycling

20.1.Lead Acid Battery Recycling

Lead acid batteries either start or power cars, trucks, buses, boats, trains, rapid mass-transit systems, recreational vehicles and electric wheelchairs all over the globe. The car battery also provides a stable electrical supply to a vehicle's electrical system.

During power outages, lead acid batteries provide quiet, pollution-free emergency power for critical operations such as air-traffic control towers, hospitals, railroad crossings, military installations, submarines, and weapons systems. In these situations the telephones stay on and this is because every major telephone company in the world, including mobile telephone service providers, uses lead acid batteries as backup power to the telecommunications systems.

Were it not for standby lead acid batteries, we probably would have power outages nearly every day because the electric utilities would not be able to handle rapid fluctuations in the demand for electricity. This is when lead acid batteries come to the rescue, as enormous arrays of batteries delivering large amounts of electricity for short periods of time until additional capacity is added to the grid.

Lead acid batteries power electric fork trucks used in warehouses, factories, mines, and ships. They also power the shuttle vehicles in airports, as well as wheelchairs, amusement park shuttles and golf carts. On the road, lead acid batteries power electric law-enforcement vehicles, buses, and very soon mail delivery vans.

20.2.Benefits of Lead Acid Battery Recycling

Why Recycle Lead acid batteries ? Unless we recycle the Lead acid spent batteries certain toxic components pose a potential risk to the environment and human health. However, recycling:

Saves Natural Resources : By making products from recycled materials instead of virgin materials, we conserve land and reduce the need to mine for more minerals.

Saves Energy : It takes less energy to make a recycled battery. In fact secondary lead bullion, for example, requires four times less energy to make than primary lead.

Saves Clean Air and Water : In most cases, making products from recycled materials creates less air pollution and water pollution than making products from virgin materials.

Saves Landfill Space : When the materials that you recycle go into new products, instead of landfills or incinerators, landfill space is conserved.

Saves Money and Creates Jobs : The recycling industry and the associated processes create

far more jobs than landfill sites or waste incinerators, and recycling is frequently the least expensive waste management option for cities and towns.

20.3.Lead Acid Battery recycling Rates

All the components of the modern lead acid battery are recyclable and from an Industry perspective lead-acid batteries are an environmental success story because in the United States just over 96% is recovered and in most of the G7 nations upwards of 95% is recycled. Compared to the usual "flagship" recycled products such as glass bottles at only 38%, aluminum cans at nearly 64% and newsprint at about 68%, lead acid batteries are the clear leaders in the field. In fact, used lead-acid batteries have topped the list of the most highly recycled consumer products for over a decade.

Unfortunately, battery recycling is not a public utility and scrap batteries are only recycled because it is profitable for the secondary non-ferrous industry to do so. In recent years, however, the introduction of essential environmental and occupational health regulations, and an all time low lead price has cut profit margins to such an extent that most secondary lead smelters that are not the beneficiaries of government levies are barely breaking even and others have closed due to severe losses.

It is increasingly important therefore for the secondary lead industry to generate as much income from a spent battery as possible in order to improve margins and maintain profitability.

Although there are some processes that smelt whole batteries most modern secondary plants break spent batteries in a mechanical hammer-mill and gravity separate the components in a series of water filled tanks.

20.4.Lead Acid Battery Recycling Loop

The earth's resources, no matter how abundant we think they are, are finite, and precious to all of us.

It is essential that the food we eat, the water we drink and the air we breathe are free of toxins and keep us healthy. Maintaining a clean environment, re-using and reclaiming resources benefits us all. Moreover, sound environmental management will support sustainable development and growth.

It is therefore in everybody's interest to recycle as much scrap material as possible, especially lead acid batteries, because if they are not recycled the materials in the battery pose a serious environmental problem and a threat to human health.

The ideal loop would be:

Lead bullion production

Battery manufacture

Recovery and recycling of the battery materials

Lead acid batteries, in whatever form, are all recyclable to a lesser or greater extent. This only means, however, that a battery can be recycled after it is spent. The battery itself does nothing to close the recycling loop if it is not recycled, but you, your governments and your industries can ensure that they enter the loop by creating an infrastructure that will promote and facilitate recycling.

20.5. Lead Acid Battery recycling options

The washed and dried polypropylene pieces are sent to a plastic recycler, where the chips are melted and extruded to produce plastic pellets for use in the manufacture of battery cases.

Although certain processes will combine the waste lead streams, the most efficient plants feed the paste to the smelting furnace to recover soft lead and the grids and terminals are sent to a melting furnace for the production of hard lead. Lead bullion from both sources will be refined, cast into ingots and sold to the battery manufacturer. The soft lead is suitable for battery paste and the hard lead bullion ideal for grids and terminals.

Polyethylene separators can be separated from the polypropylene waste stream and recycled, although in most secondary plants the current practice is to use this waste as a fuel supplement.

Used battery acid can be handled in four ways: Neutralized, and the resulting effluent treated to meet clean water standards and then released into the public sewer system.

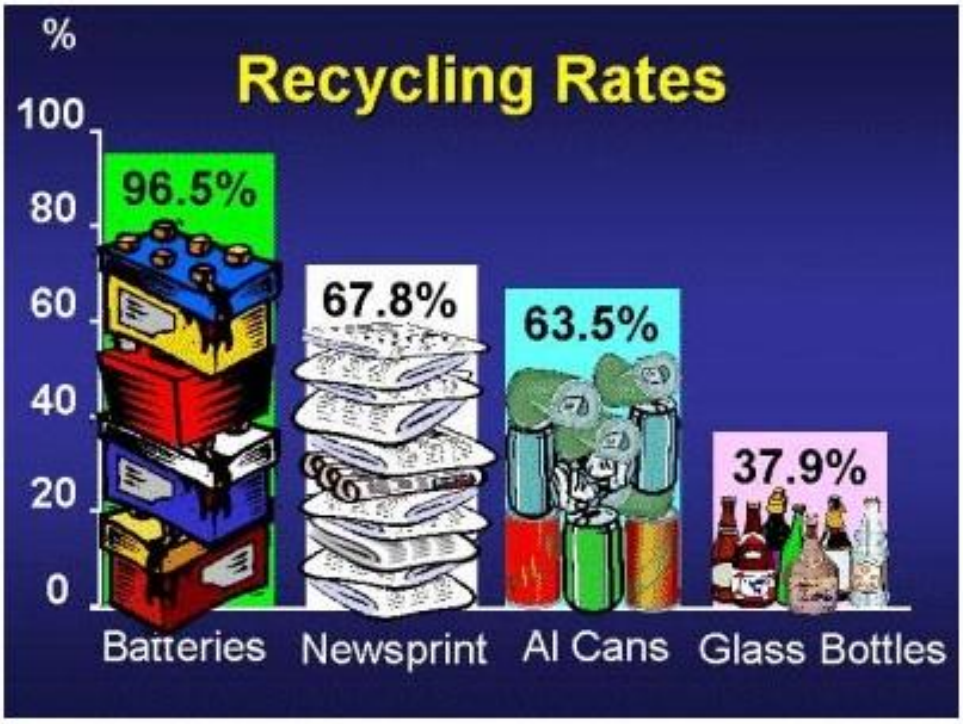
Reclaimed and after topping up with concentrated acid then used as the electrolyte in new batteries

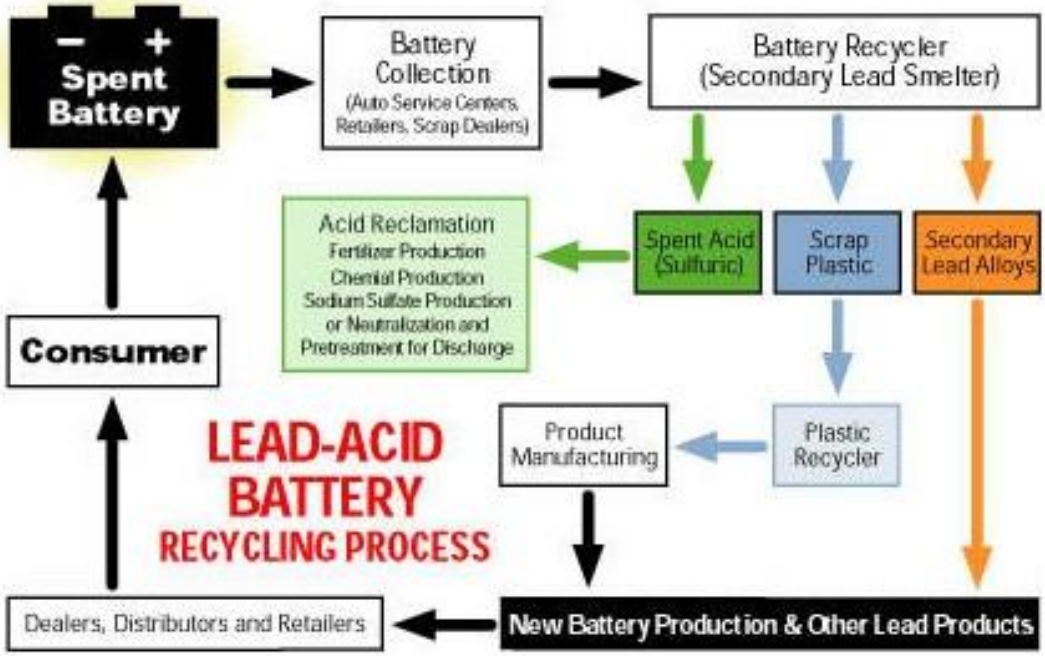
Chemically treated and converted to either agricultural fertilizer using ammonia or to powered sodium sulfate for use in either glass and textile manufacturing or as a filler or stabilizer in household laundry detergent.

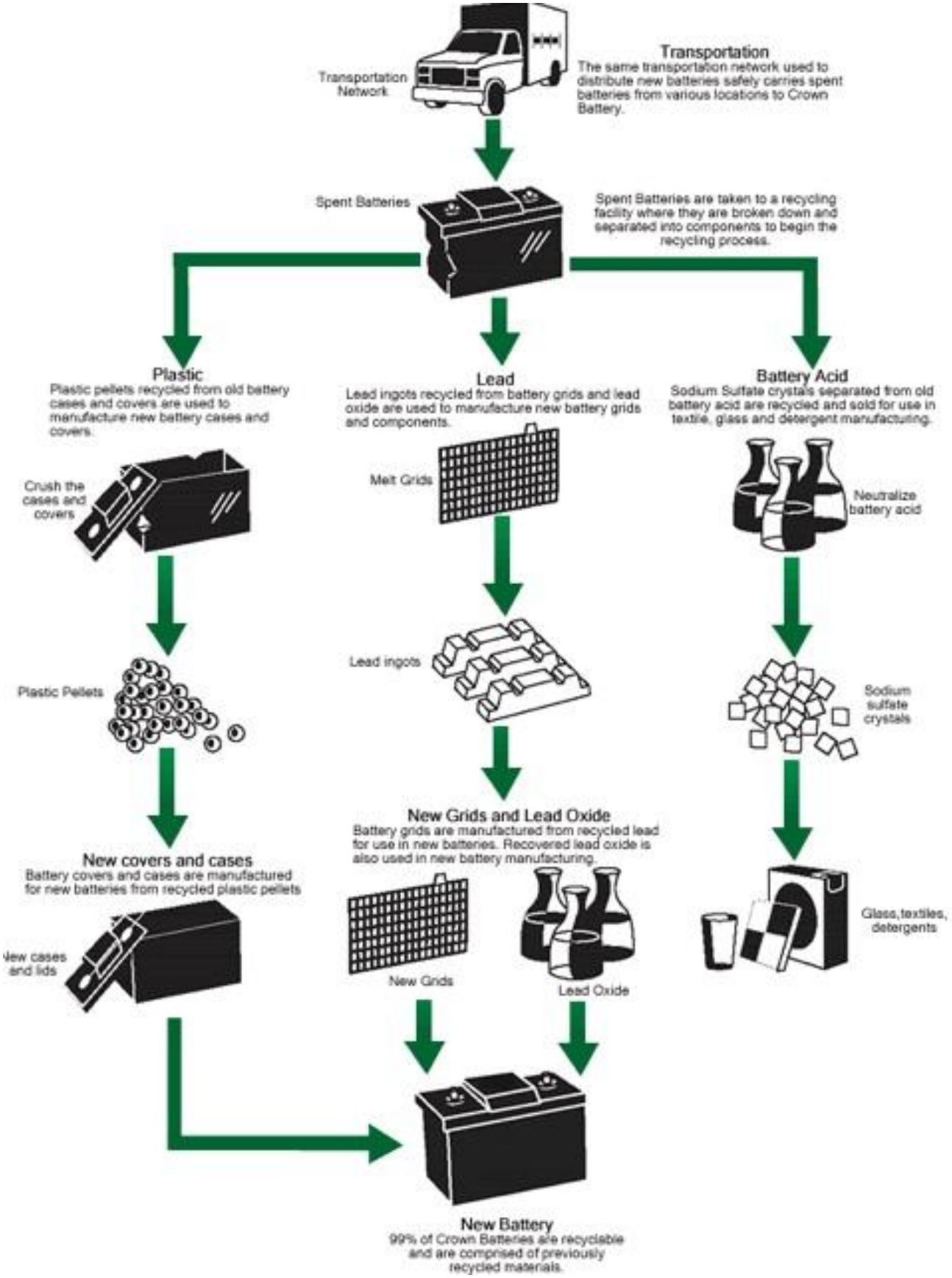
Converted to gypsum for use in the production of cement or by the construction industry in the manufacture of fiber board.

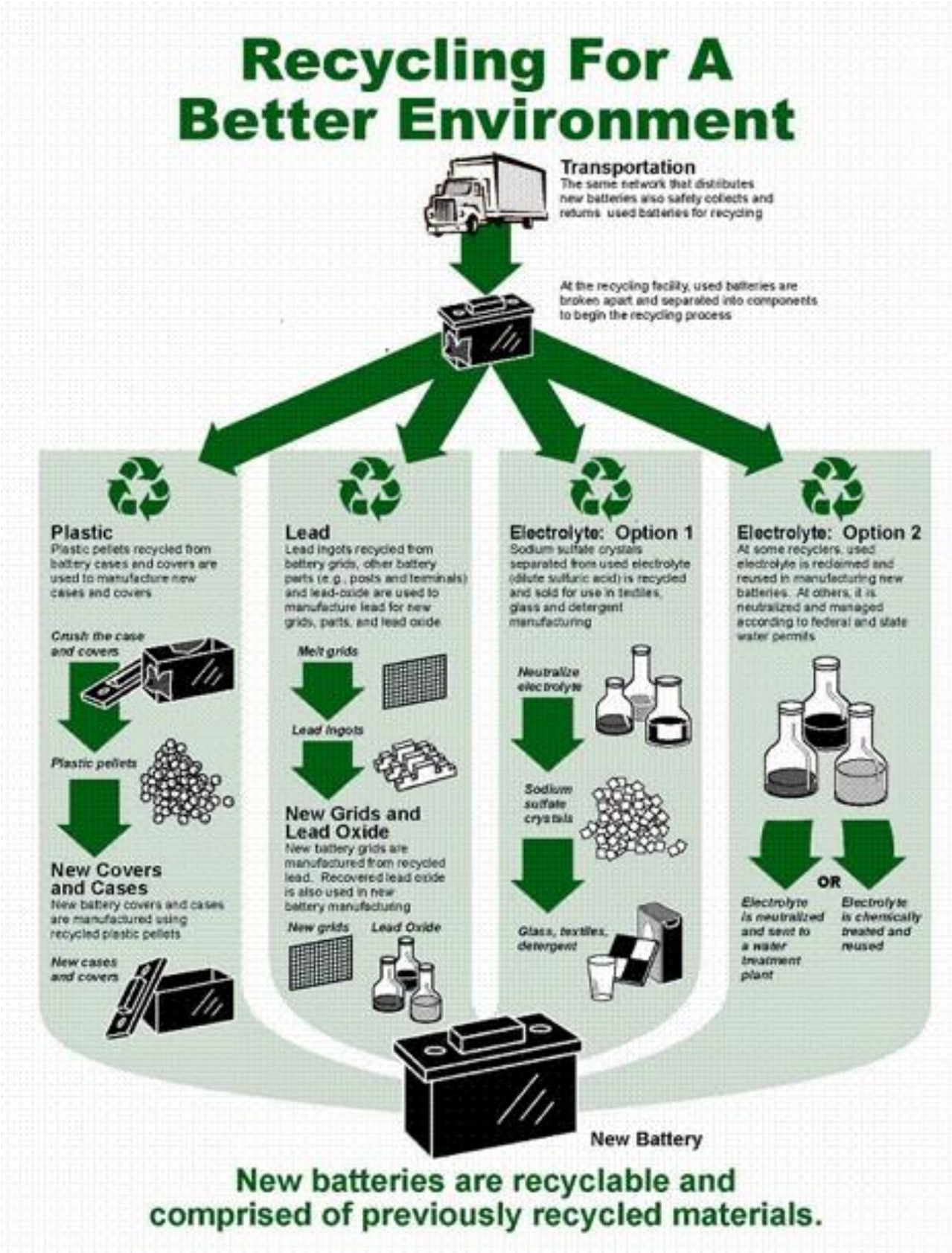
Plastic Container	< Plastic Recycler
Lead Plates	< Paste to the smelter
	< Grids to melting furnace
Lead Terminals	< To the melting furnace
Plate Separators	< Recycler/fuel source
Acid Electrolyte	< Neutralized & discharged
	< Reclaimed
	< Fertilizer, soap stabilizer
	< Fiber Board

20.6 Figures


%
Recycling Rates
100
80
60
40
20
0
96.5%
67.8%
63.5%
37.9%
Batteries
Newsprint
Al Cans
Glass Bottles


Spent Battery
Battery Collection
(Auto Service Centers, Retailers, Scrap Dealers)
Battery Recycler (Secondary Lead Smelter)
Acid Reclamation
Fertilizer Production
Chemical Production
Sodium Sulfate Production
or Neutralization and Pretreatment for Discharge
Spent Acid (Sulfuric)
Scrap Plastic
Secondary Lead Alloys
Consumer
LEAD-ACID BATTERY
RECYCLING PROCESS
Product Manufacturing
Plastic Recycler
Dealers, Distributors and Retailers
New Battery Production & Other Lead Products


Transportation Network
Transportation
The same transportation network used to distribute new batteries safely carries spent batteries from various locations to Crown Battery.
Spent Batteries
Spent Batteries are taken to a recycling facility where they are broken down and separated into components to begin the recycling process.
Plastic
Plastic pellets recycled from old battery cases and covers are used to manufacture new battery cases and covers.
Lead
Lead ingots recycled from battery grids and lead oxide are used to manufacture new battery grids and components.
Battery Acid
Sodium Sulfate crystals separated from old battery acid are recycled and sold for use in textile, glass and detergent manufacturing.
Crush the cases and covers
Melt Grids
Neutralize battery acid
Plastic Pellets
Lead ingots
Sodium sulfate crystals
New Grids and Lead Oxide
Battery grids are manufactured from recycled lead for use in new batteries. Recovered lead oxide is also used in new battery manufacturing.
New covers and cases
Battery covers and cases are manufactured for new batteries from recycled plastic pellets
New cases and lids
New Grids
Lead Oxide
Glass, textiles, detergents
New Battery
99% of Crown Batteries are recyclable and are comprised of previously recycled materials.


Recycling For A Better Environment
Transportation
The same network that distributes new batteries also safely collects and returns used batteries for recycling
At the recycling facility, used batteries are broken apart and separated into components to begin the recycling process
Plastic
Plastic pellets recycled from battery cases and covers are used to manufacture new cases and covers
Crush the case and covers
Plastic pellets
New Covers and Cases
New battery covers and cases are manufactured using recycled plastic pellets
New cases and covers
Lead
Lead ingots recycled from battery grids, other battery parts (e.g., posts and terminals) and lead-oxide are used to manufacture lead for new grids, parts, and lead oxide
Melt grids
Lead ingots
New Grids and Lead Oxide
New battery grids are manufactured from recycled lead. Recovered lead oxide is also used in new battery manufacturing
New grids
Lead Oxide
Electrolyte: Option 1
Sodium sulfate crystals separated from used electrolyte (dilute sulfuric acid) is recycled and sold for use in textiles, glass and detergent manufacturing
Neutralize electrolyte
Sodium sulfate crystals
Glass, textiles, detergent
Electrolyte: Option 2
At some recyclers, used electrolyte is reclaimed and reused in manufacturing new batteries. At others, it is neutralized and managed according to federal and state water permits
OR
Electrolyte is neutralized and sent to a water treatment plant
Electrolyte is chemically treated and reused
New Battery
New batteries are recyclable and comprised of previously recycled materials.


LEAD-ACID BATTERIES
ENDLESSLY RECYCLABLE!
AN ENVIRONMENTAL SUCCESS STORY
BY RECYCLING LEAD-ACID BATTERIES, WE'RE PLAYING AN IMPORTANT ROLE IN MAKING THE WORLD A SAFER, HEALTHIER PLACE. THE LEAD AND PLASTIC IN USED BATTERIES FROM CARS AND OTHER VEHICLES CAN BE RECYCLED AGAIN AND AGAIN AS NEW BATTERIES AND OTHER PRODUCTS WE USE EVERY DAY.
RECYCLING NOT ONLY PROTECTS THE ENVIRONMENT BUT HELPS SAVE ENERGY AND RAW MATERIALS.
WWW.GOPHERRESOURCE.COM
WHEN A DEAD BATTERY IS REMOVED FROM A VEHICLE, IT BEGINS A LIFE CYCLE THAT'S REPEATED MANY, MANY TIMES.
THE USED BATTERY IS SHIPPED TO GOPHER RESOURCE.
Gopher Resource
LEAD
PLASTIC
ACID
AFTER THE BATTERY IS CRUSHED, THE PIECES ARE SEPARATED INTO 3 MAIN COMPONENTS- LEAD, PLASTIC AND ACID.
ACID IS NEUTRALIZED AND RE-CLAIMED
MELTED PLASTIC CHIPS ARE SHAPED INTO TINY PELLETS AND SHIPPED TO MANUFACTURERS FOR NEW USES.
IN SMELTING FURNACES, RECLAIMED LEAD IS MELTED AND REFINED.
REFINED LEAD IS POURED INTO MOLDS AND COOLED.
WE SHIP OUR REFINED LEAD TO MANUFACTURERS NATIONWIDE.
Gopher Resource
LEAD PARTS ARE COMBINED WITH A RECYCLED PLASTIC CASING TO PRODUCE A NEW BATTERY
THE CYCLE BEGINS AGAIN...

21. Literature

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